

Attorney Docket No. 044463-0336

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants: Vincent L. CHIANG et al.

Title: PRODUCTION OF SYRINGYL LIGNIN IN GYMNOSPERMS

Appl. No.: 10/681,878

Filing Date: October 9, 2003

Examiner: Stuart F. Baum

Art Unit: 1638

DECLARATION UNDER 37 C.F.R. § 1.132

Commissioner for Patents
Washington, D.C. 20231

Sir:

The undersigned, William H. Rottmann, hereby declares as follows:

1. I received my Ph.D. degree in Biochemistry in 1985 from the University of California, Berkeley. I have worked in the field of plant genetics since December 1984. Previously, I was a Senior Research Scientist at Westvaco/MeadWestvaco in Summerville, South Carolina. Currently I am a Senior Scientist at ArborGen and I am an expert in the area of gene regulation in wood development and flowering in trees. A copy of my resume is attached as Exhibit A.

2. I submit this declaration to establish that the promoter sequence claimed in the present invention is novel over the prior art and is adequately described in the specification. I additionally submit this declaration to establish that the specification of the present application provides extensive information to enable the person skilled in the art to make and/or use the claimed invention, because the sequence claimed in the present application comprises the necessary elements essential for promoter binding and activity.

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3. I understand that the U.S. Patent and Trademark Office's position is that the Applicants of the present invention have not shown that the claimed 4CL1B promoter has promoter activity and have not specified the length and sequence of the promoter region which are essential for promoter activity.

4. I disagree with the U.S. Patent and Trademark Office's position. The promoter sequence claimed in the present application, SEQ ID NO: 11, corresponds to the 4CL1B promoter, which is described in Example 5 as being 2.3 kb in size. It is common usage among scientists to refer to genomic DNA fragments that comprise upstream regulatory regions and a portion of the 5'-untranslated region of the transcribed region as "promoter fragments". However, the 5'-untranslated region is not considered part of the promoter and can be eliminated in synthetic constructs to drive transcription of a different gene.

5. I assert that the cDNA sequence of a pine 4CL published by Voo *et al.* (*Plant Physiol.* 108: 85-95. 1995) can be used by one skilled in the art to verify that SEQ ID NO: 11 is a pine (and, therefore, gymnosperm) 4CL DNA sequence. The 100% identity found in the 142 base pair overlap with SEQ ID NO: 11 indicates that the two sequences are the same gene. Additionally, the cDNA sequence allows the skilled artisan to know where the 5'-untranslated sequence is. The promoter for the 4CL gene clearly lies upstream of base number 2107 of SEQ ID NO 11, where the match with the cDNA begins.

6. I further state that the cDNA sequence provided by Voo *et al* does not specify sequences sufficient for gene expression. I know of no examples where a plant cDNA sequence or segment thereof is sufficient to direct gene expression. In particular the CCAAT and TATA Box motifs, found upstream of the transcribed region, are missing from the cDNA sequence disclosed in Voo *et al.*

7. SEQ ID NO: 11 has two possible CCAAT-like motifs (positions 2018 – 2021 and 2014 – 2044) and two possible TATA motifs (positions 2037–2040 and 2066–2069) upstream of the 5'-untranslated region. The prior art does not provide these sites.

8. I further declare that since the 2001 filing date of this application, three different pine 4CL promoter fragments were tested in transgenic plants using the GUS reporter gene at ArborGen. Each of these promoter fragments showed xylem-preferred expression of the reporter gene. The first promoter fragment was the 2.3 kb sequence provided as SEQ ID NO: 11. The second promoter fragment was an approximately 1630 bp fragment of a *Pinus radiata* 4CL promoter with very high sequence similarity to SEQ ID NO: 11. The alignment of the 4CL1B promoter and the *Pinus radiata* 4CL promoter is attached herein as Exhibit B. The aligned sequences show great similarity in several regions and are over 95% identical in the segments corresponding to bases 630-1254 and 1404-2221 regions of SEQ ID NO: 11. The third promoter fragment was a 659 bp fragment of the same *Pinus radiata* promoter. The 659 bp *Pinus radiata* promoter fragment was 98.5% identical to the 659 bp fragment of SEQ ID NO: 10 disclosed in the present application.

9. A publication by Goicoechea *et al.* (*The Plant Journal* 43: 553-567 (2005)) is attached herein as Exhibit C. This publication shows that the MYB2 transcription factor isolated from *Eucalyptus gunnii* specifically binds to cis-regulatory regions in two lignin biosynthetic genes through a G(G/T)T(A/T)GGT(A/G) binding site.

10. I assert that all three pine 4CL promoter fragments and subfragments described above include the two GGTAGGTA motifs predicted to be MYB binding sites involved in promoter specificity according to Goicoechea *et al.* These motifs begin at position 1802 of SEQ ID NO: 11, and one of ordinary skill in the art would expect that DNA segments beginning after these motifs would not be able to specify xylem expression. These data confirm that the sequence claimed in the present application comprises the necessary elements essential for promoter binding and activity.

11. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Respectfully submitted,

Date Mar 19, 2007

By William H. Rottmann

William H. Rottmann
Senior Scientist,
ArborGen, Summerville, SC

EXHIBIT A

WILLIAM H. ROTTMANN

PROFESSIONAL EXPERIENCE:

- 1/03 - present Senior Scientist, ArborGen, Summerville, SC. (Gene discovery related to wood development in pine, eucalyptus, and cottonwood.)
- 10/98 – 12/02 Senior Research Scientist, Westvaco/MeadWestvaco, Summerville, SC. (Regulation of flowering in pine and cottonwood.)
- 11/95 - 10/98 Research Scientist, Westvaco, Summerville, SC. (Regulation of flowering in pine and cottonwood.)
- 2/91 - 10/95 Research Associate in the laboratory of Steven H. Strauss, Department of Forest Science, Oregon State University, Corvallis OR. (Isolation and characterization of cDNAs and genes expressed during development of cottonwood inflorescences.)
- 3/88 - 1/91 Research Geneticist in the laboratory of Athanasios Theologis, Plant Gene Expression Center, Albany, CA. (Isolation and characterization of cDNAs and genes from tomato that encode ACC synthase, a key enzyme in ethylene biosynthesis.)
- 12/84 - 1/88 National Science Foundation Postdoctoral Fellow in the laboratory of David M. Lonsdale, Institute for Plant Sciences Research (formerly Plant Breeding Institute), Cambridge, England. (Isolation and sequence analysis of mitochondrial gene responsible for male sterility in maize.)
- 8/78 - 12/84 Graduate Research Assistant in the laboratory of Edward E. Penhoet, Department of Biochemistry, UC Berkeley. (Isolation and sequence analysis of cDNAs and genes for human aldolases.)

EDUCATION:

- Ph.D. 1985. University of California, Berkeley. Biochemistry. Thesis title: Evolution of human aldolases.
- B.S. 1978. State University of New York at Stony Brook. Biochemistry (highest honors).

PEER-REVIEWED PUBLICATIONS:

- Nehra, N.S., Becwar, M.R., Rottmann, W.H., Pearson, L., Chowdhury, K., Chang, S., Wilde, H.D., Kodrzycki, R.J., Zhang, C., Gause, K.C., Parks, D.W., Hinchee M.A. 2005. Forest Biotechnology: Innovative Methods, Emerging Opportunities. In Vitro Cell. Devel. Biol. – Plant 41: 701-717.
- Rottmann, W.H., Meilan, R., Sheppard, L.A., Brunner, A.M., Skinner, J.S., Ma, C., Cheng, S., Jouanin, L., Pilate, G., and Strauss, S.H. 2000. Diverse effects of overexpression of *LEAFY* and *PTLF*, a poplar (*Populus*) homolog of *LEAFY/FLORICAULA*, in transgenic poplar and *Arabidopsis*. Plant J. 22: 235-245.
- Brunner, A.M., Rottmann, W.H., Sheppard, L.A., Krutovskii, K., DiFazio, S.P., Leonardi, S., and Strauss, S.H. 2000. Structure and expression of duplicate *AGAMOUS* orthologues in poplar. Plant Molec. Biol. 44: 619-634.
- Sheppard, L.A., Brunner, A.M., Krutovskii, K.V., Rottmann, W.H., Skinner, J.S., Vollmer, S.S., and Strauss, S.H. 2000. A *DEFICIENS* homolog from the dioecious tree *Populus trichocarpa* is expressed in both female and male floral meristems of its two-whorled, unisexual flowers. Plant Physiol. 241: 627-639.
- Brunner, A.M., Mohamed, R., Meilan, R., Sheppard, L.A., Rottmann, W.H., and Strauss, S.H. 1998. Genetic engineering of sexual sterility in shade trees. J. Arbor. 24: 263-273.
- Hipkins, V.D., Marshall, K., Neale, D.B., Rottmann, W.H., and Strauss, S.H. 1995. A mutation hotspot in the chloroplast genome of a conifer (Douglas-fir: *Pseudotsuga*) is caused by variability in the number of direct repeats derived from a partially duplicated tRNA gene. Curr. Genet. 27: 572-579.
- Strauss, S.H., Rottmann, W.H., Brunner, A.M., and Sheppard, L.A. 1995. Genetic engineering of sterility in trees. Mol. Breeding 1: 5-26.

PATENTS AWARDED

- US 6,444,877. Rottmann, W.H. 2002. Liquidambar styraciflua AGAMOUS (LSAG) gene.
- US 6,395,892. Strauss, S.H., Rottmann, W., Brunner, A., and Sheppard, L. 2002. Floral homeotic genes for manipulation of flowering in poplar and other plant species.

EXHIBIT B

| | | | | | Section 1 | |
|-----------------------|-------|---|-----|-----|-----------|-----|
| Pr4CLPromoter(1650bp) | (1) | 1 | 10 | 20 | 30 | 44 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (1) | GGCCGGGTGGTGACATTTATTCTATAAATTCACTCTCAAAACAAAGA | | | | |
| | | | | | Section 2 | |
| Pr4CLPromoter(1650bp) | (45) | 45 | 50 | 60 | 70 | 88 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (45) | AGGATTACAAAAATAAAAGAAAACAAAATTTCATCTTAACA | | | | |
| | | | | | Section 3 | |
| Pr4CLPromoter(1650bp) | (89) | 89 | 100 | 110 | 120 | 132 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (89) | TAATTATAATTGTGTTCACAAAATTCAAACCTAAACCCCTTAATA | | | | |
| | | | | | Section 4 | |
| Pr4CLPromoter(1650bp) | (133) | 133 | 140 | 150 | 160 | 176 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (133) | TAAAGAATTCTTTCAACAATACACTTAATCACAACTTCTTC | | | | |
| | | | | | Section 5 | |
| Pr4CLPromoter(1650bp) | (177) | 177 | 190 | 200 | 210 | 220 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (177) | ATCACAAACCTCCTCCAACAAAATTAAAATAGATTAATAAAATAAA | | | | |
| | | | | | Section 6 | |
| Pr4CLPromoter(1650bp) | (221) | 221 | 230 | 240 | 250 | 264 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (221) | TAAACTTAACTATTAAAAAAAAATTATAACAAAATTATTAA | | | | |
| | | | | | Section 7 | |
| Pr4CLPromoter(1650bp) | (265) | 265 | 270 | 280 | 290 | 308 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (265) | AACTTCAAAATAAACAAACTTTTATACAAAATTCAAAACT | | | | |
| | | | | | Section 8 | |
| Pr4CLPromoter(1650bp) | (309) | 309 | 320 | 330 | 340 | 352 |
| SEQ ID NO 11 | (1) | ----- | | | | |
| Consensus | (309) | TTAAAAATAAGCTAACACTGAAAATGTGAGTACATTAAAAGG | | | | |

Section 9

| | | | | | |
|-----------------------|--|-----|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (353) 353 | 360 | 370 | 380 | 396 |
| | (1) | | | | |
| SEQ ID NO 11 | (353) ACGCTGATCACAAAAATTTGAAAACATAAACAAACTGAAACT | | | | |
| Consensus | (353) | | | | |

Section 10

| | | | | | |
|-----------------------|--|-----|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (397) 397 | 410 | 420 | 430 | 440 |
| | (1) | | | | |
| SEQ ID NO 11 | (397) CTACCTTTAAGAACATGAGTTGTCGTCTCATTAACCTATTAGTT | | | | |
| Consensus | (397) | | | | |

Section 11

| | | | | | |
|-----------------------|--|-----|-----|-------|------------|
| Pr4CLPromoter(1650bp) | (441) 441 | 450 | 460 | 470 | 484 |
| | (1) | | | | |
| SEQ ID NO 11 | (441) TTATAGTTCGAACATTAACGTATCTTTATTTATGGAAATA | CCC | GGG | CTGGT | TCTTATGGAA |
| Consensus | (441) | C | CT | TAT | TTATGGAA |

Section 12

| | | | | | |
|-----------------------|---|---|-------------------------------------|-----|-----|
| Pr4CLPromoter(1650bp) | (485) 485 | 490 | 500 | 510 | 528 |
| | (22) | - - - G T T T T T A A A T A T A T - - - | A T T T T T T G G G T T G A G T T T | | |
| SEQ ID NO 11 | (485) AGGGTGT T T T A A T A A G T G A T T T G G G A T T T T T A G T - - A A T T T | | | | |
| Consensus | (485) GT T T T A A T A T A T T G T A T T T T T G T A T T T T T | | | | |

Section 13

| | | | | | |
|-----------------------|---|---|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (529) 529 | 540 | 550 | 560 | 572 |
| | (58) | A C T T A A A A T T T G G A A A A G - G T T G G T A A G A A C - - T A T A A A T T G A | | | |
| SEQ ID NO 11 | (527) A T T T G T G A T A T G T T A T G G A G T T T T A A A A A T A T A T A T A T A T A | | | | |
| Consensus | (529) A T T A T G A G T T A A A A A T A T A T A T A T A T A | | | | |

Section 14

| | | | | | |
|-----------------------|---|---|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (573) 573 | 580 | 590 | 600 | 616 |
| | (98) | T T G A G T T G T G A A T - G A G T G T T T A T G G A T T T T T A A - - G A T G T T | | | |
| SEQ ID NO 11 | (571) T A T A T T T T G G G T T G A G T T T A C T T A A A A T T T G G A A A A G G T T G G T | | | | |
| Consensus | (573) T A T T T G G G T T G A G T T T A C T T A A A A T T T G G A A A A G G T T G G T | | | | |

Section 15

| | | | | | |
|-----------------------|---|---|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (617) 617 | 630 | 640 | 650 | 660 |
| | (139) | A A - A T T T A T A T A T G T A G T T G T G A A G G A G T G T T T A T G G A T T T T | | | |
| SEQ ID NO 11 | (615) A A G A A C T A T A A A T T G A G T T G T G A A T G A G T G T T T A T G G A T T T T | | | | |
| Consensus | (617) A A A T A T A T A T G T G A A G A T G T G T T T A T G G A T T T T | | | | |

Section 16

| | | | | | |
|-----------------------|---|---|-----|-----|-----|
| Pr4CLPromoter(1650bp) | (661) 661 | 670 | 680 | 690 | 704 |
| | (182) | T A A G A T G T T A A A T G T G T A T A T G T A A T T A A A A T T T A T T T G A A T | | | |
| SEQ ID NO 11 | (659) T A A G A T G T T A A A T T T A T A T A T G T A A T T A A A A T T T A T T T G A A T | | | | |
| Consensus | (661) T A A G A T G T T A A A T T A T G T A A T T A A A A T T T A T T T G A A T | | | | |

Section 17

| | | | | | | |
|-----------------------|-------|---|----------------|----------------|-----|-----|
| | (705) | 705 | 710 | 720 | 730 | 748 |
| Pr4CLPromoter(1650bp) | (226) | AACAAAAAATTATAATTGGATAAAAAAT | - | GTTTGTTAAATTAA | | |
| SEQ ID NO 11 | (703) | AACAAAAA-TTATAATTGGATAAAAAATTGTTGTAAATTAA | | | | |
| Consensus | (705) | AACAAAAA TTATAATTGGATAAAAAAT | GTTTGTTAAATTAA | | | |

Section 18

| | | | | | | |
|-----------------------|-------|--|-----|-----|-----|-----|
| | (749) | 749 | 760 | 770 | 780 | 792 |
| Pr4CLPromoter(1650bp) | (269) | GAGTAAAAATTAAAATCTAAAATAATTAAACACTATTATT | | | | |
| SEQ ID NO 11 | (746) | GAGTAAAAATTCTAAAATCTAAAATAATTAAACACTATTATT | | | | |
| Consensus | (749) | GAGTAAAAATTT AAAATCTAAAATAATTAAACACTATTATT | | | | |

Section 19

| | | | | | | |
|-----------------------|-------|--|-----|----------|-----|-----|
| | (793) | 793 | 800 | 810 | 820 | 836 |
| Pr4CLPromoter(1650bp) | (313) | TAAAAAAATTGTTGGTAAATTATCTTAAATTAA | - | GTTAAAAT | | |
| SEQ ID NO 11 | (790) | TAAAAAAATTGTTGGTAAATTATCTTAAATTAAAGTTAAAAT | | | | |
| Consensus | (793) | TAAAAAAATTGTTGGTAAATTATCTTA ATTAA GTTAAAAT | | | | |

Section 20

| | | | | | | |
|-----------------------|-------|---|-----|-----|-----|-----|
| | (837) | 837 | 850 | 860 | 870 | 880 |
| Pr4CLPromoter(1650bp) | (356) | TTAGAAAAAAATAATTAAATTAAACTTTGAAGTC | | | | |
| SEQ ID NO 11 | (834) | TTAGAAAAAAAT - TAATTAAATTAAATAAAACTTTGAAGTC | | | | |
| Consensus | (837) | TTAGAAAAAA TAATTAAATTAA TAAACTTTGAAGTC | | | | |

Section 21

| | | | | | | |
|-----------------------|-------|--|-----|-----|-----|-----|
| | (881) | 881 | 890 | 900 | 910 | 924 |
| Pr4CLPromoter(1650bp) | (400) | ATATTCCAAATGTTCCAAAATATTAAATTCAATTGACATTCA | | | | |
| SEQ ID NO 11 | (876) | ATATTCCAAATATTTCAAAATATTAAATTCTATTGCAATTCA | | | | |
| Consensus | (881) | ATATTCCAAAT TTTCCAAAATATTAAAT ATTTCATTCA | | | | |

Section 22

| | | | | | | |
|-----------------------|-------|---|-----|-----|-----|-----|
| | (925) | 925 | 930 | 940 | 950 | 968 |
| Pr4CLPromoter(1650bp) | (444) | AAATACAATTAAATAACAAAACCTTCATGAAATAGATTAAACCAA | | | | |
| SEQ ID NO 11 | (920) | AAATACAATTAAATAATAAAACCTTCATGAAATAGATTAAACCAA | | | | |
| Consensus | (925) | AAATACAATTAAATAA AAAACCTTCATG AATAGATTAAACCAA | | | | |

Section 23

| | | | | | | |
|-----------------------|-------|--|-----|-----|------|------|
| | (969) | 969 | 980 | 990 | 1000 | 1012 |
| Pr4CLPromoter(1650bp) | (488) | TTTGTATGAAAACCAAAAACTCTCAAATAAAATTAAATTACAAA | | | | |
| SEQ ID NO 11 | (964) | TTTGTATAAAACCAAAAACTCTCAAATAAAATTAAATTACAAA | | | | |
| Consensus | (969) | TTTGTAT AAAACCAAAAACTCTCAAATAAAATTAAATTACAAA | | | | |

Section 24

| | | | | | | |
|-----------------------|--------|---|------|------|------|------|
| | (1013) | 1013 | 1020 | 1030 | 1040 | 1056 |
| Pr4CLPromoter(1650bp) | (532) | ATATTATTAAACATTATGATTCAAGAAAAGAGAATAACCAGTTTC | | | | |
| SEQ ID NO 11 | (1008) | ACATTATCAACATTATGATTCAAGAAAAGACAATAACCAGTTTC | | | | |
| Consensus | (1013) | A ATTAT AACATTATGATTCAAGAAAAGA AATAACCAGTTTC | | | | |

Section 25

| | | | | |
|-------------|------|------|------|------|
| (1057) 1057 | 1070 | 1080 | 1090 | 1100 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (576) CAATAAAATAAAA -- CCTCATGGCTGGTAATTAAAGATCTCATT
SEQ ID NO 11 (1052) CAATAAAATAAAAAACCTCATGGCCCGTAATTAAAGATCTCATT
Consensus (1057) CAATAAAATAAAA CCTCATGGC GTAATTAAAGATCTCATT

Section 26

| | | | | |
|-------------|------|------|------|------|
| (1101) 1101 | 1110 | 1120 | 1130 | 1144 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (618) ATTAATTCTTATTTTTAATTTTTACATAGAAAATATCTTTA
SEQ ID NO 11 (1096) ATTAATTCTTATTTTTAATTTTTACATAGAAAATATCTTTA
Consensus (1101) ATTAATTCTTATTTTTAATTTTTACATAGAAAATATCTTTA

Section 27

| | | | | |
|-------------|------|------|------|------|
| (1145) 1145 | 1150 | 1160 | 1170 | 1188 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (662) TATTATATACGAGAAATATAGAATGTTCTAGTCCAAGGACTATT
SEQ ID NO 11 (1140) TATTGTATCCAAGAAATATAGAATGTTCTCGTCCAGGGACTATT
Consensus (1145) TATT TAT C AGAAATATAGAATGTTCT GTCCA GGACTATT

Section 28

| | | | | |
|-------------|------|------|------|------|
| (1189) 1189 | 1200 | 1210 | 1220 | 1232 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (706) AATTTCCAAATAAGTTCAAAATCATTACATTAAACTCATCAT
SEQ ID NO 11 (1184) AATCTCCAAACAAGTTCAAAATCATTACATTAAAGCTCATCAT
Consensus (1189) AAT TCCAAA AAGTTCAAAATCATTACATTAAA CTCATCAT

Section 29

| | | | | |
|-------------|------|------|------|------|
| (1233) 1233 | 1240 | 1250 | 1260 | 1276 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (750) GTCATTTGTGGATGGAAATTAGAC --- AAAAGAGAA -----
SEQ ID NO 11 (1228) GTCATTTGTGGATGGAAATTATATTGTATAAGAGAAATATAGA
Consensus (1233) GTCATTTGTGGATGGAAATTA A A AAGAGAA

Section 30

| | | | | |
|-------------|------|------|------|------|
| (1277) 1277 | 1290 | 1300 | 1310 | 1320 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (784) ----- TCC --- CAAAT -----
SEQ ID NO 11 (1272) ATGTTCTCGTCTAGGGACTATTAAATTCCAAACAAATTCAAAA
Consensus (1277) TCC CAAAT

Section 31

| | | | | |
|-------------|------|------|------|------|
| (1321) 1321 | 1330 | 1340 | 1350 | 1364 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (792) -- ATTTCTCTCAATCTC -----
SEQ ID NO 11 (1316) TCATTACATTAAAGCTCATCATGTCATTGTGGATTGGAAATTA
Consensus (1321) ATT C T AA CTC

Section 32

| | | | | |
|-------------|------|------|------|------|
| (1365) 1365 | 1370 | 1380 | 1390 | 1408 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (807) -- CCAAAATAAACCTAATT----- ATATA
SEQ ID NO 11 (1360) GACAAAAAAAATCCCAAATATTCTCTCAATCTCCAAAATATA
Consensus (1365) C AAAA AA CC AA TA ATATA

Section 33

| | | | | |
|-------------|------|------|------|------|
| (1409) 1409 | 1420 | 1430 | 1440 | 1452 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (830) GTTCGAACCTCCATATTTGGAAATTGAGAATTTTCTACCAA
SEQ ID NO 11 (1404) GTTCGAACCTCCATATTTGGAAATTGAGAATTTTCTACCAA
Consensus (1409) GTTCGAACCTCCATATTTGG AATTGAGAATTTT TACCAA

Section 34

| | | | | |
|-------------|------|------|------|------|
| (1453) 1453 | 1460 | 1470 | 1480 | 1496 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (874) TAATATATTTTTTATACATTTAGAGATTTCCAGACATATT
SEQ ID NO 11 (1448) TAATATATTTTTT - ATACATTTAGAGATTTCCAGACATATT
Consensus (1453) TAATATATTTTTT ATACATTTAGAGATTTCCAGACATATT

Section 35

| | | | | |
|-------------|------|------|------|------|
| (1497) 1497 | 1510 | 1520 | 1530 | 1540 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (918) TGCTCTGGGATTATTGGAAATGAAGGTTGAGTAATGAAGGTT
SEQ ID NO 11 (1491) TGCTCTGGGATTATTGGAAATGAAGGTT
Consensus (1497) TGCTCTGGGATTATTGGAAATGAAGGTT

Section 36

| | | | | |
|-------------|------|------|------|------|
| (1541) 1541 | 1550 | 1560 | 1570 | 1584 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (962) GAGTTATAAACTTCAGTAATCCAAGTATCTCGGTTTTGAAG
SEQ ID NO 11 (1519) GAGTTATAAACTTCAGTAATCCAAGTATCTCGGTTTTGAAG
Consensus (1541) GAGTTATAAACTTCAGTAATCCAAGTATCTCGGTTTTGAAG

Section 37

| | | | | |
|-------------|------|------|------|------|
| (1585) 1585 | 1590 | 1600 | 1610 | 1628 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (1006) ATACTAAATCCATTATATAATAAAAAACACATTAAACACCAAT
SEQ ID NO 11 (1563) ATACTAAATCCATTATATAATAAAAAACACATTAAACACCAAT
Consensus (1585) ATACTAAATCCATTATATAATAAAAAACACATTAAACACCAAT

Section 38

| | | | | |
|-------------|------|------|------|------|
| (1629) 1629 | 1640 | 1650 | 1660 | 1672 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (1050) TTAAATGGGATTTCAGATTGTATCCCAGTGTATTGGCTAACCA
SEQ ID NO 11 (1607) TTAAATGGGATTTCAGATTGTATCCCAGTGTATTGGCTAACCA
Consensus (1629) TTAAATGGGATTTCAGATTGTATCCCAGTGTATTGGCTAACCA CA

Section 39

| | | | | |
|-------------|------|------|------|------|
| (1673) 1673 | 1680 | 1690 | 1700 | 1716 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (1094) TTTTCTTATTGTAATCTAACCAATTCCAATTCCGCCCTGGTG
SEQ ID NO 11 (1651) TTTTCTTATTGTAATCTAACCAATTCTAACCAATTCCACCTGGTG
Consensus (1673) TTTTCTTATTGTAATCTAACCAATTCTAACCAATTCA ATTTC CCCTGGTG

Section 40

| | | | | |
|-------------|------|------|------|------|
| (1717) 1717 | 1730 | 1740 | 1750 | 1760 |
|-------------|------|------|------|------|

Pr4CLPromoter(1650bp) (1138) TGAACGTGACTGACAAATGCGGCCGAAAACAGCGAATGAAATGT
SEQ ID NO 11 (1695) TGAACGTGACTGACAAATGCGGTCCGAAAACAGCGAATGAAATGT
Consensus (1717) TGAACGTGACTGACAAATGCGG CCGAAAACAGCGAATGAAATGT

Section 41

| | | | | | |
|--------|------|------|------|------|------|
| (1761) | 1761 | 1770 | 1780 | 1790 | 1804 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1182) CTGGGTGATCGGTCAAACAAGCGGTGGCGAGAGAACGC GGTTG
SEQ ID NO 11 (1739) CTGGGTGATCGGTCAAACAAGCGGTGGCGAGAGAGCGC GGGTG
Consensus (1761) CTGGGTGATCGGTCAAACAAGCGGTGGCGAGAGA CGCGGGTG

Section 42

| | | | | | |
|--------|------|------|------|------|------|
| (1805) | 1805 | 1810 | 1820 | 1830 | 1848 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1226) TTGGCCTAGCCGGATGGGGTAGGTAGACGGCGTATTACCGGC
SEQ ID NO 11 (1783) TTGGCCTAGCCGGATGGGGTAGGTAGACGGCGTATTACCGGC
Consensus (1805) TTGGCCTAGCCGGATGGGGTAGGTAGACGGCGTATTACCGGC

Section 43

| | | | | | |
|--------|------|------|------|------|------|
| (1849) | 1849 | 1860 | 1870 | 1880 | 1892 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1270) GAGTTGTCCGAATGGAGTTTCGGGGTAGGTAGTAACGTAGACG
SEQ ID NO 11 (1827) GAGTTGTCCGAATGGAGTTTCGGGGTAGGTAGTAACGTAGACG
Consensus (1849) GAGTTGTCCGAATGGAGTTTCGGGGTAGGTAGTAACGTAGACG

Section 44

| | | | | | |
|--------|------|------|------|------|------|
| (1893) | 1893 | 1900 | 1910 | 1920 | 1936 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1314) TCAATGGAAAAAGTCATAATCTCCGTCAAAATCCAACCGCTCC
SEQ ID NO 11 (1871) TCAATGGAAAAAGTCATAATCTCCGTCAAAATCCAACCGCTCC
Consensus (1893) TCAATGGAAAAAGTCATAATCTCCGTCAAAATCCAACCGCTCC

Section 45

| | | | | | |
|--------|------|------|------|------|------|
| (1937) | 1937 | 1950 | 1960 | 1970 | 1980 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1358) TTCACATCGCAGAGTTGGTGGCCACGGGACCCCTCCACCCACTCA
SEQ ID NO 11 (1915) TTCACATCGCAGAGTTGGTGGCCACGGGACCCCTCCACCCACTCA
Consensus (1937) TTCACATCGCAGAGTTGGTGGCCACGGGACCCCTCCACCCACTCA

Section 46

| | | | | | |
|--------|------|------|------|------|------|
| (1981) | 1981 | 1990 | 2000 | 2010 | 2024 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1402) CTCAATCGATCGCCTGCCGTGGTTGCCATTATTCAACCATAACG
SEQ ID NO 11 (1959) CTC ---- GATCGCCTGCCGTGGTTGCCATTATTCAACCATAACG
Consensus (1981) CTC GATCGCCTGCCGTGGTTGCCATTATTCAACCATAACG

Section 47

| | | | | | |
|--------|------|------|------|------|------|
| (2025) | 2025 | 2030 | 2040 | 2050 | 2068 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1446) CCACTTGACTCTCACCAACAATTCCAGGCCGGCTTCGAGACA
SEQ ID NO 11 (1999) CCACTTGACTCTCACCAACAATTCCAGGCCGGCTTCATACA
Consensus (2025) CCACTTGACTCTCACCAACAATTCCAGGCCGGCTTC A ACA

Section 48

| | | | | | |
|--------|------|------|------|------|------|
| (2069) | 2069 | 2080 | 2090 | 2100 | 2112 |
|--------|------|------|------|------|------|

Pr4CLPromoter(1650bp)(1490) ATGTACTGCACAGGAAAATCCAATATAAAAGGCCGGCTCCGCT
SEQ ID NO 11 (2043) ATGTACTGCACAGGAAAATCCAATATAAAAGGCCGGCTCTGCT
Consensus (2069) ATGTACTGCACAGGAAAATCCAATATAAA GCCGGCCTC GCT

Section 49

(2113) 2113 2120 2130 2140 2156
Pr4CLPromoter(1650bp)(1534) TCCTTCTCAGTAGCCCCCAGCTCATTCAGTTCTTCCACTGCAG
SEQ ID NO 11 (2087) TCCTTCTCAGTAGCCCCCAGCTCATTCATCAATTCTTCCACTGCAG
Consensus (2113) TCCTTCTCAGTAGCCCCCAGCTCATTCATCA TTCTTCCACTGCAG

Section 50

(2157) 2157 2170 2180 2190 2200
Pr4CLPromoter(1650bp)(1578) GCTACATTGTCAGACACGTTTCCGCCATTTCGCCTGTTTC
SEQ ID NO 11 (2131) GCTACATTGTCAGACACGTTTCCGCCATTTCGCCTGTTTC
Consensus (2157) GCTACATTGTCAGACACGTTTCCGCCATTTCGCCTGTTTC

Section 51

(2201) 2201 2210 2220 2230 2244
Pr4CLPromoter(1650bp)(1622) TGCGGAGAATTGATCAGGTTACCCATGG-----
SEQ ID NO 11 (2175) TGCGGAGAATTGATCAGGTTCGGATTGGGATTGAATCAATTGA
Consensus (2201) TGCGGAGAATTGATCAGGTT TGG

Section 52

(2245) 2245 2250 2260 2277
Pr4CLPromoter(1650bp)(1651) -----
SEQ ID NO 11 (2219) AAGGTTTTATTTCAAGTATTCGATGCCATG
Consensus (2245)

EXHIBIT C

EgMYB2, a new transcriptional activator from *Eucalyptus* xylem, regulates secondary cell wall formation and lignin biosynthesis

Monica Goicoechea^{1,†}, Eric Lacombe^{1,†}, Sylvain Legay¹, Snejzana Mihaljevic¹, Philippe Rech¹, Alain Jauneau¹, Catherine Lapierre², Brigitte Pollet², Daniel Verhaegen³, Nicole Chaubet-Gigot¹ and Jacqueline Grima-Pettenati^{1,*}

¹Institut Fédératif de Recherches FR40, Unité mixte de Recherches 5546, Université Paul Sabatier—Centre National de la Recherche Scientifique, Pôle de Biotechnologie Végétale, 24 chemin de Borde Rouge, BP 17 Auzeville, 31326 Castanet-Tolosan, France,

²Laboratoire de Chimie Biologique, Unité mixte de Recherches 206, Institut National de la Recherche Agronomique-Institut National Agronomique, 78850 Thiverval-Grignon, France, and

³CIRAD Forêt, TA 10/C Baillarguet BP 5035, 34398 Montpellier Cédex 05, France

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*For correspondence (fax +33 562 193 502; e-mail grima@scsv.ups-tlse.fr).

†Both authors contributed equally to this work.

Summary

EgMYB2, a member of a new subgroup of the R2R3 MYB family of transcription factors, was cloned from a library consisting of RNA from differentiating *Eucalyptus* xylem. *EgMYB2* maps to a unique locus on the *Eucalyptus grandis* linkage map and co-localizes with a quantitative trait locus (QTL) for lignin content. Recombinant *EgMYB2* protein was able to bind specifically the *cis*-regulatory regions of the promoters of two lignin biosynthetic genes, cinnamoyl-coenzyme A reductase (*CCR*) and cinnamyl alcohol dehydrogenase (*CAD*), which contain MYB consensus binding sites. *EgMYB2* was also able to regulate their transcription in both transient and stable expression assays. Transgenic tobacco plants over-expressing *EgMYB2* displayed phenotypic changes relative to wild-type plants, among which were a dramatic increase in secondary cell wall thickness, and an alteration of the lignin profiles. Transcript abundance of genes encoding enzymes specific to lignin biosynthesis was increased to varying extents according to the position of individual genes in the pathway, whereas core phenylpropanoid genes were not significantly affected. Together these results suggest a role for *EgMYB2* in the co-ordinated control of genes belonging to the monolignol-specific pathway, and therefore in the biosynthesis of lignin and the regulation of secondary cell wall formation.

Keywords: MYB, transcription, xylem, lignin, secondary cell wall.

Introduction

Lignin is one of the major components of the secondary walls of xylem cells, allowing mechanical support and efficient conduction of water and solutes over long distances within the vascular system. In woody plant species, a large proportion of photosynthetically assimilated carbon is channelled to lignin synthesis and, as a consequence, lignified cell walls represent a major proportion of plant biomass and a huge reservoir of carbon stored within the polymers of lignocelluloses (Boudet *et al.*, 2003).

Lignin biosynthesis involves the phenylpropanoid pathway, which converts phenylalanine to *p*-coumaroyl

coenzyme A (CoA), the precursor of a wide range of phenolic compounds. The enzymes involved in this short sequence are *L*-phenylalanine ammonia-lyase (PAL), cinnamate 4-hydroxylase (C4H) and 4-coumarate: CoA ligase (4CL) (Figure 1). The subsequent hydroxylation and methylation steps have recently been shown to occur at the level of hydroxycinnamic acid esters and their corresponding aldehydes and/or alcohols (Humphreys and Chapple, 2002). The most likely route for the production of monolignols probably involves enzymatic reactions catalysed by *p*-hydroxy-cinnamoyl CoA: quinate/shikimate *p*-hydroxycinnamoyl

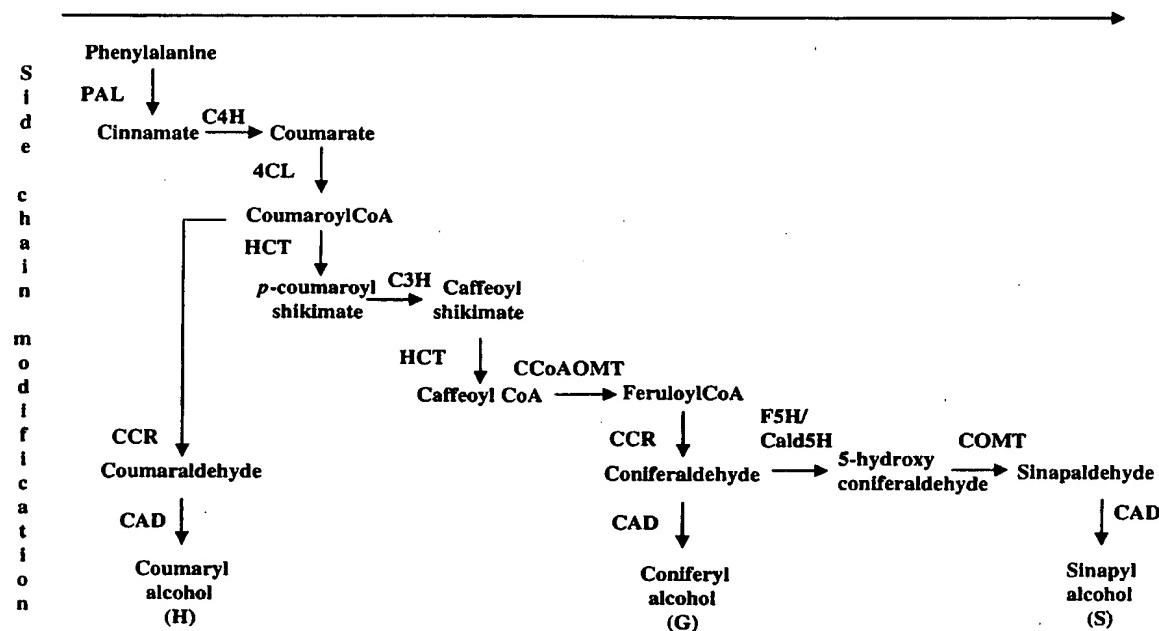


Figure 1. Model of monolignol biosynthesis pathway in angiosperms. Enzymes involved in side-chain modification: PAL, phenylalanine ammonia-lyase; 4CL, 4-coumarate CoA ligase; HCT, *p*-hydroxycinnamoyl CoA: shikimate *p*-hydroxyltransferase; CCR, cinnamoyl CoA reductase; CAD, cinnamyl alcohol dehydrogenase. SAD, sinapyl alcohol dehydrogenase. Enzymes involved in ring modification: C4H, cinnamate 4-hydroxylase; C3H, coumaroyl-quinate/shikimate 3-hydroxylase; CCoAOMT, caffeoyl CoA O-methyl transferase; F5H, ferulate 5-hydroxylase or Cald5H, coniferaldehyde-5-hydroxylase; COMT, caffeic acid/5-hydroxyferulic acid O-methyltransferase. The coumaryl, coniferyl and sinapyl alcohols are transported to the cell wall and polymerized to give rise to hydroxyphenyl (H), guaiacyl (G) and sinapyl (S) lignin, respectively.

transferase (HCT); coumaroyl-quinate/shikimate 3-hydroxylase (C3H); caffeoyl CoA O-methyltransferase (CCoAOMT); ferulate 5-hydroxylase (F5H, also called coniferaldehyde 5-hydroxylase, Cald5H); and caffeic acid O-methyltransferase (COMT) (for a review see Boerjan *et al.*, 2003) (Figure 1). Cinnamoyl-CoA reductase (CCR) and cinnamyl alcohol dehydrogenase (CAD) catalyse the two last reductive steps leading to the three monolignols (*p*-coumaryl, coniferyl and syringyl alcohols), the monomeric units incorporated into the lignin heteropolymer.

In an attempt to gain insight into the mechanisms underlying the spatial and temporal control of lignification, we have characterized the genes encoding the terminal enzymes of lignin biosynthesis, CCR and CAD, and studied their expression during development. The promoters of the two genes from *Eucalyptus gunnii* (*EgCCR* and *EgCAD2*) direct expression in vascular tissues undergoing active lignification and preferentially in differentiating xylem (Feuillet *et al.*, 1995; Lacombe *et al.*, 2000; Lauvergeat *et al.*, 2002). The close correlation between *EgCCR* and *EgCAD2* promoter activities and lignification supports the view that tissue-specific transcription of these genes is a key step controlling the sites of lignin accumulation. Dissection of

those promoters identified a *cis*-regulatory region of about 50–70 bp, responsible for driving this specific expression pattern in both promoters. The DNA–protein interaction sites have been mapped, and contain an AC-rich element corresponding to the MYB transcription factor binding consensus motif MBSIIIG (MYB-binding site IIIG, Lacombe *et al.*, 2000; Romero *et al.*, 1998; Sivadon and Grima-Pettenati, 2004).

The family of MYB transcription factors is one of the most abundant classes of transcription factors in plants, and the subfamily containing the two-repeat R2R3 DNA-binding domain is the largest (Stracke *et al.*, 2001). Some R2R3 MYB proteins bind AC elements found in the promoters of several genes of the phenylpropanoid pathway (Grotewold *et al.*, 1994; Sablowski *et al.*, 1994), and it has been suggested that these common motifs may provide a mechanism by which different steps of phenylpropanoid metabolism are co-ordinately regulated (Douglas, 1996; Martin and Paz-Ares, 1997; Weisshaar and Jenkins, 1998). Indeed, a number of R2R3 MYB proteins have been assigned functions in the regulation of phenylpropanoid biosynthesis and shown to regulate the biosynthesis of phenolic compounds, including lignin (Borevitz *et al.*, 2000; Jin *et al.*, 2000; Patzlaff *et al.*,

2003; Tamagnone *et al.*, 1998). Other transcription factors might also be involved (Rogers and Campbell, 2004).

As part of a programme aimed at characterizing 'lignin-specific' MYB trans-activators, we have cloned R2R3 MYB factors from a cDNA library of RNA from *Eucalyptus* differentiating xylem. Here we report the cloning and functional characterization of a new R2R3MYB gene, *EgMYB2*, which is able to bind the *EgCCR* and *EgCAD2* gene regulatory regions and to regulate their transcription. Transgenic tobacco plants over-expressing *EgMYB2* exhibited an increase in secondary wall thickness and an alteration in lignin composition. All the genes involved in the monolignol-specific biosynthesis pathway were upregulated, whereas the expression of core phenylpropanoid genes was not significantly affected. Taken together, the results reported here suggest that *EgMYB2* is a positive regulator of secondary cell wall formation and lignin biosynthesis.

Results

Eucalyptus EgMYB2 defines a new subgroup of the R2R3 MYB family

To isolate MYB transcription factors potentially implicated in the regulation of lignin biosynthesis, we screened an *E. gunnii* xylem cDNA library (Lacombe *et al.*, 1997) with a MYB consensus sequence corresponding to the highly conserved amino acid sequence in the R3 repeat of the DNA-binding domain (Jackson *et al.*, 1991). Here we focus on the characterization of *EgMYB2* (AJ576023), a cDNA 1410 bp in length encoding a 321 amino acid protein (35.5 kDa, pI 4.92) which exhibits typical features of the R2R3 MYB protein family (Figure 2). The R2R3 DNA-binding domain comprises two imperfect repeats (54 and 51 amino acids, respectively), and has the predicted helix-turn-helix structures containing the conserved tryptophan residues involved in DNA binding (Martin and Paz-Ares, 1997). The predicted *EgMYB2* protein is closely related to other MYB proteins from different species within the R2R3 domain (Figure 2a,c) and shares the greatest homology with a *Populus trichocarpa* MYB protein *Poptr1:49071* (86.4% similarity); and a MYB protein from Arabidopsis, *AtMYB83* (85.9% similarity; Romero *et al.*, 1998). Also closely related to *EgMYB2* are a MYB protein from a monocot species, *Hordeum vulgare* HvSPYMYB, *AtMYB46* and *Poptr1:64485*. A high level of homology was also found with a gymnosperm MYB protein, the pine PtMYB4, which was recently shown to regulate lignin biosynthesis (Patzlaff *et al.*, 2003). *EgMYB2* belongs to group C as defined by Romero *et al.* (1998), most members of which bind preferentially to MBSIIIG motifs G/g/T/t/G/G/T/g.

The C-terminal domain of the *EgMYB2* protein does not contain any of the small conserved motifs used by Kranz *et al.* (1998) to classify MYB proteins in 22 subgroups. However,

alignment of the C-terminal domain of *EgMYB2* with its closest related MYB proteins, *Poptr1:49071* and *AtMYB83* (Figure 2b), revealed a conserved amino acid motif NX(R/K)(I/M)G(E/D)WDL(E/D)GL(M/I)(D/E)XXXSFPFLDF in the extreme C-terminal part of the protein. The presence of this C-terminal motif may define a new subgroup of MYB proteins, which possibly reflects the similar functions of its members.

EgMYB2 maps to a unique locus on the Eucalyptus grandis linkage map and co-localizes with a QTL for lignin content

The existence of a single *EgMYB2* gene in the *Eucalyptus* genome was supported by Southern hybridization at high stringency using the 3' end as a probe (data not shown) and by genetic mapping. A full sib family of 201 interspecific hybrids between *Eucalyptus urophylla* and *E. grandis* was used to localize *EgMYB2* onto linkage maps previously constructed for both parents using RAPD markers (Verhaegen and Plomion, 1996; Verhaegen *et al.*, 1997). Using the single-strand conformation polymorphism (SSCP) technique (Orita *et al.*, 1989), *EgMYB2* was mapped on linkage group 2 of the *E. grandis* map (Figure 3). Interestingly, *EgMYB2* co-localizes with a quantitative trait locus (QTL) accounting for 4.5% of the variation in lignin content ($P = 0.009$). Although no linkage was found with the *E. urophylla* markers, a segregation (1:1:1:1) of the *EgMYB2* parental alleles was observed in the progeny. Using an ANOVA procedure between the four segregation classes, it was possible to discern a significant increase in *EgMYB2* maternal and paternal allele effects, explaining up to 7% of the variation of lignin content ($P = 0.005$).

EgMYB2 is preferentially expressed in differentiating xylem tissue

Using quantitative RT-PCR on *Eucalyptus* tissues, *EgMYB2* was shown to be preferentially expressed in the differentiating secondary xylem of stem and root, and in the central vein isolated from mature leaves (Figure 4). It is also expressed, albeit to a lesser extent, in the young part of stems and in young leaves containing developing veins. *EgMYB2* transcripts were present at very low levels in stem phloem, mature leaf blades, root bark and young lateral roots. This expression profile in lignin-rich tissue, which is in agreement with the fact that *EgMYB2* had been cloned from a *Eucalyptus* xylem cDNA library, could suggest that *EgMYB2* is involved in the regulation of lignin biosynthesis. Therefore we tested the effects of *EgMYB2* on two possible targets, the specific monolignol biosynthetic genes *EgCCR* and *EgCAD2*, which were also shown to be highly and preferentially expressed in *Eucalyptus* differentiating xylem (Grima-Pettenati *et al.*, 1993; Lacombe *et al.*, 1997).

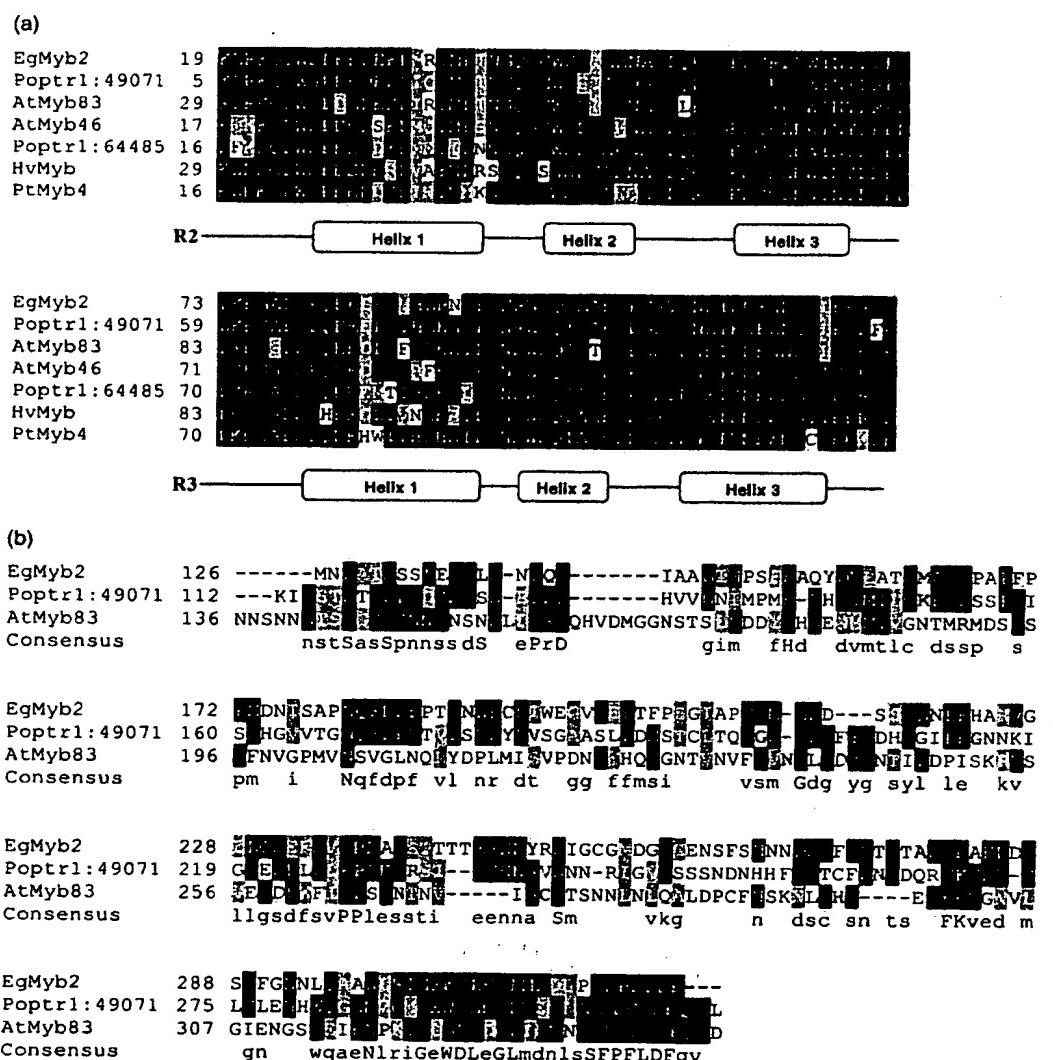


Figure 2. Sequence analysis of the *EgMYB2* protein.

(a) Amino acid sequence alignment of the R2R3 domains of *EgMYB2* and other plant R2R3 MYB proteins. Multiple sequence alignments were generated using CLUSTALW (Thompson *et al.*, 1994). Residues highlighted in black are identical in more than 50% of the sequences; those highlighted in grey indicate conserved amino acid substitutions. The boxes below the alignment represent the predicted helix structure composing the two repeats.

(c) Phylogenetic analysis of the R2R2 domain of *EgMYB2*. Neighbour-joining trees generated by MEGA 5.05 with the JTT matrix, a bootstrap of 1000 replicates, and a tree distance of 0.01.

(c) Phylogenetic analysis of the R2R3 domain of EgMYB2. Neighbour joining tree generated with MEGA 2.1 (Kumar *et al.*, 2001) using 1000 random sequence-addition bootstrap replication.

Genbank accession numbers: *EgMYB2* (AJ576023), *AfMYB48* (NM121290), *AfMYB83* (NM111685), *PtMYB4* (AY356371), *AmMYB4* (NM120023), *HmMYB3* (X70881), *HvSPYMYB* (AY672068), *LdMYB1* (X95297), *AmMYB61* (NP172425), *AmMYB55* (AF176000), *DnMYB2* (AF485893); *PoMYB1* (AF07171) and *PoMYB1-S4495* were found in the *S. fas-*

draft of the *Populus trichocarpa* genome (<http://genome.jgi-psf.org/Poptr1/Poptr1.home.html>).

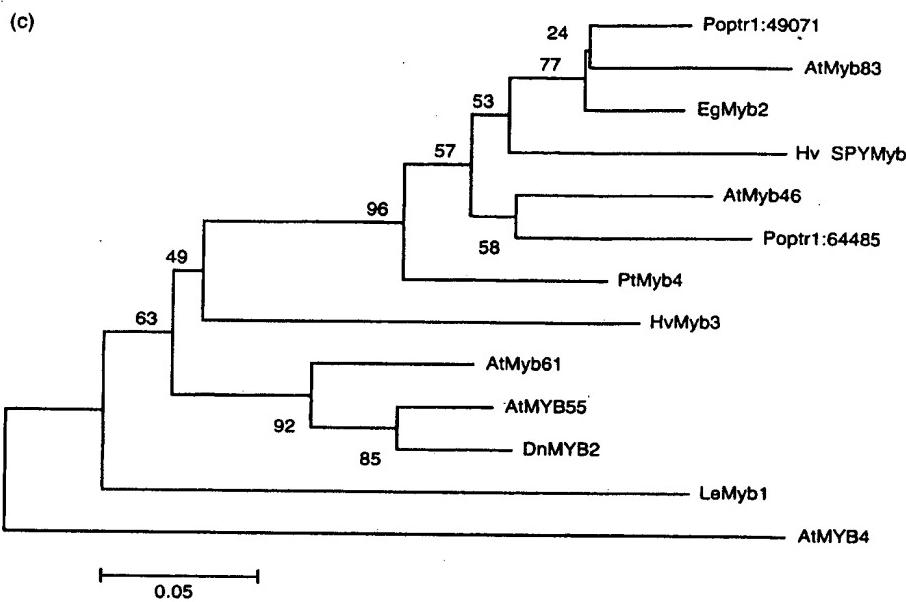


Figure 2. Continued.

EgMYB2 specifically binds the cis-regulatory regions of the EgCCR and EgCAD2 promoters

As a first step to evaluate whether EgMYB2 is involved in the transcriptional regulation of the *EgCCR* and *EgCAD2* genes, we tested the ability of EgMYB2 to bind their *cis*-regulatory regions (Figure 5a) which contain MBSIIIG sites (Figure 5b). For this purpose, the EgMYB2 cDNA was fused to the glutathione-S-transferase coding sequence (GST) and expressed in *Escherichia coli* cells. Purified GST-EgMYB2 protein was tested in electrophoretic mobility-shift assay (EMSA) for its ability to bind the cognate regulatory regions of *EgCAD2* (-203 to -129) and *EgCCR* (-119 to -70) promoters (Lacombe *et al.*, 2000; Lauvergeat *et al.*, 2002).

As shown in Figure 5(c), EMSA experiments revealed that EgMYB2 is able to bind to both the *EgCAD2* (Figure 5c, lane 1) and *EgCCR* (Figure 5c, lane 5) promoter fragments. No DNA-binding activity was observed when using recombinant GST alone (data not shown), indicating that the interaction occurs specifically with EgMYB2. A 100-fold molar excess of unlabelled non-specific DNA fragment had no effect on the complex formation (Figure 5c, lanes 3 and 8), whereas effective competition was observed using either *EgCAD2* or *EgCCR* promoter fragments as specific competitors (Figure 5c, lanes 2 and 6). Cross-competition experiments have also been performed (Figure 5c, lanes 4 and 7), showing the ability of the *EgCAD2* and *EgCCR* promoter

regions to compete reciprocally with the EgMYB2 protein for binding. These gel-shift experiments show that recombinant EgMYB2 is able to bind specifically *in vitro* to the regulatory regions of the *EgCCR* and *EgCAD2* promoters. These results raise the possibility that EgMYB2 could control the co-ordinated expression of these two genes involved in the monolignol biosynthetic pathway.

EgMYB2 acts as a transcriptional activator of EgCCR and EgCAD2 promoters *in vivo*

To test whether EgMYB2 could transcriptionally regulate *EgCCR* and *EgCAD2* genes *in vivo*, the *EgCCR* and *EgCAD2* promoters fused to the GUS gene were used as reporter constructs (Lacombe *et al.*, 2000; Lauvergeat *et al.*, 2002) (Figure 6a). Each was co-transfected by *Agrobacterium* infiltration of *Nicotiana tabacum* (tobacco) leaves with an effector construct under the control of the 35S CaMV promoter, containing either the EgMYB2 cDNA (referred to as *EgMyb2⁺*), or the EgMYB2 DNA-binding domain only (referred to as *EgMyb2⁻*) (Figure 6a). Control values obtained using an effector construct without the EgMYB2 gene (pJR1) exhibited significant levels of GUS activity. Interestingly, when *EgCCR* and *EgCAD2* promoters were co-transfected with *EgMYB2⁺* construct, an induction of GUS activity was observed (Figure 6b). This increase was obtained reproducibly in several independent experiments, and was slightly higher for *EgCAD2* (2.4-fold) than for *EgCCR*.

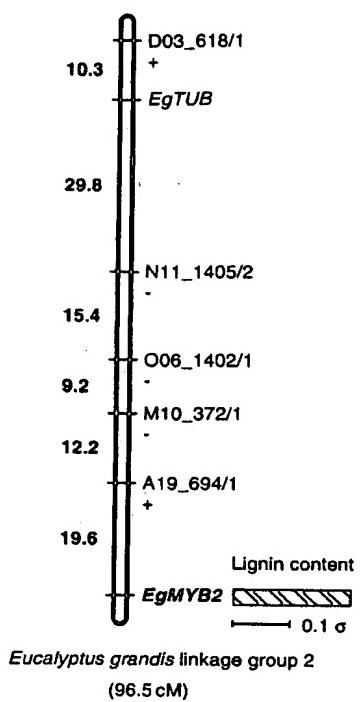


Figure 3. Genetic mapping of *EgMYB2* on *Eucalyptus* RAPD maps. Using the single-strand conformation polymorphism (SSCP) technique, *EgMYB2* was located on *Eucalyptus grandis* linkage group 2 (for detailed maps see Verhaegen and Plomion, 1996). Distances along the linkage group are Kosambi centimorgans (cM); framework markers were ordered with an interval support ≥ 2 . *EgMYB2* co-localizes with a QTL peak accounting for 4.5% of the phenotypic variation of the lignin content. *EgMYB2* effect is shown in cross-hatched bars expressed as phenotypic standard deviation (σ , difference between favourable QTL genotype and population mean).

(1.8-fold). Student's tests showed the relevance of these transactivation levels with significant values of $P < 0.001$ and $P < 0.04$ for transactivation of *EgCAD* and *EgCCR* promoters, respectively. The C-terminal region of *EgMYB2* appears to be the domain responsible for transcriptional activation of both promoters, as no activation was found using the *EgMYB2⁻* effector construct which contains only the DNA-binding domain.

Phenotypic changes induced by ectopic expression of *EgMYB2* in transgenic tobacco

To gain an insight into the role of *EgMYB2* in *plants*, we generated 18 independent transgenic tobacco plants expressing *EgMYB2* under the control of the 35S promoter (*EgMyb2⁺*), and 15 dominant negative mutants expressing only the DNA-binding domain (*EgMyb2⁻*).

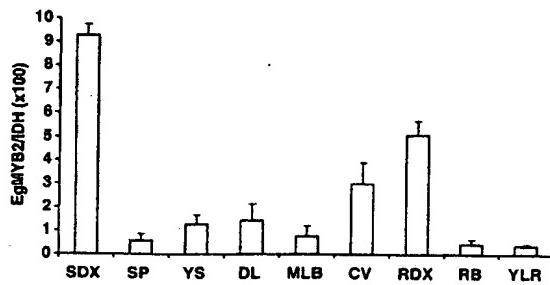


Figure 4. Expression of *EgMYB2* in *Eucalyptus* tissues. Expression of *EgMYB2* was monitored by quantitative RT-PCR on RNA extracted from tissues of glasshouse-grown *Eucalyptus globulus*: stem differentiating secondary xylem, SDX; stem phloem, SP; young stems, YS; developing leaves, DL; mature leaf blades, MLB; central veins, CV; main root differentiating xylem, RDX; bark, RB; young lateral roots, YLR. Results are expressed as number of molecules ($\times 100$) relative to *EgIDH* expression level as internal standard (see Experimental procedures). Two replicates were conducted using three independent biological individuals. Means and standard deviations are shown.

When grown *in vitro*, there were no obvious developmental differences among the primary transformants and control plants. After transfer to the glasshouse, *EgMyb2⁺* plants still showed no visible differences in growth and/or phenotypic aspect relative to control plants, whereas *EgMyb2⁺* plants exhibited a number of phenotypic differences (Figure 7). Half the plants transformed with the *EgMyb2⁺* construct (9/18) grew to only two-thirds of the size of the control plants (Figure 7a). Many of the *EgMyb2⁺* plants had two main stems emerging at the base of the plant (11/18) (Figure 7b), an effect generally associated with a loss of apical dominance. Interestingly, in hand-cut stem sections most plants also exhibited orange coloration of the xylem ring compared with the yellowish xylem of control plants (Figure 7c), probably reflecting an alteration of the secondary cell wall composition. Five independent primary transformants (2.7; 2.16; 2.18; 2.19; 2.24), all exhibiting orange-coloured xylem, were selected for study of segregation of the transgene in the progeny. Like most of the *EgMyb2⁺* plants they showed a significant reduction in seed production compared with controls, and the seeds were paler. Moreover, seeds of three transformants (2.18; 2.19; 2.24) were unable to germinate despite repeated attempts involving changes to the sterilization treatment, and even with no sterilization treatment at all. The percentage of germination of seeds from transformants 2.7 and 2.16 were 50 and 75%, respectively.

As a first step towards understanding why the seed did not germinate at all, or with a dramatically reduced efficiency, lignin staining was performed using phloroglucinol on seeds from control plants and transformants 2.7 and 2.18 (Figure 7d-f). Approximately half the seeds of transformant 2.7 stained more intensely than the control seeds, in

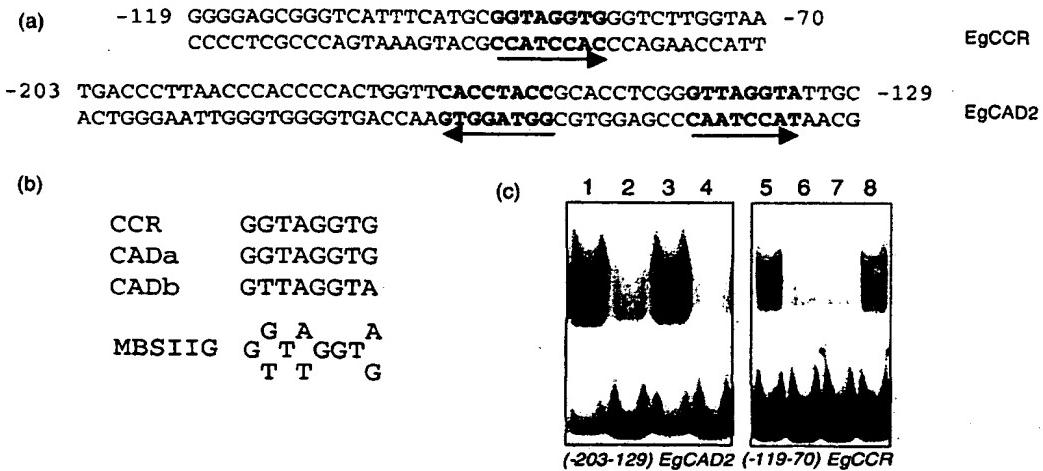


Figure 5. Binding of EgMYB2 to the *cis*-regulatory regions of the *EgCAD2* and *EgCCR* promoters.

(a) Nucleotide sequences of *EgCAD2* and *EgCCR* promoter fragments used in electrophoretic mobility-shift assay (EMSA) experiments. These fragments correspond to the *cis*-regulatory regions involved in vascular expression. Positions given with respect to transcription start site. AC elements indicated in bold with arrows indicating their orientation.

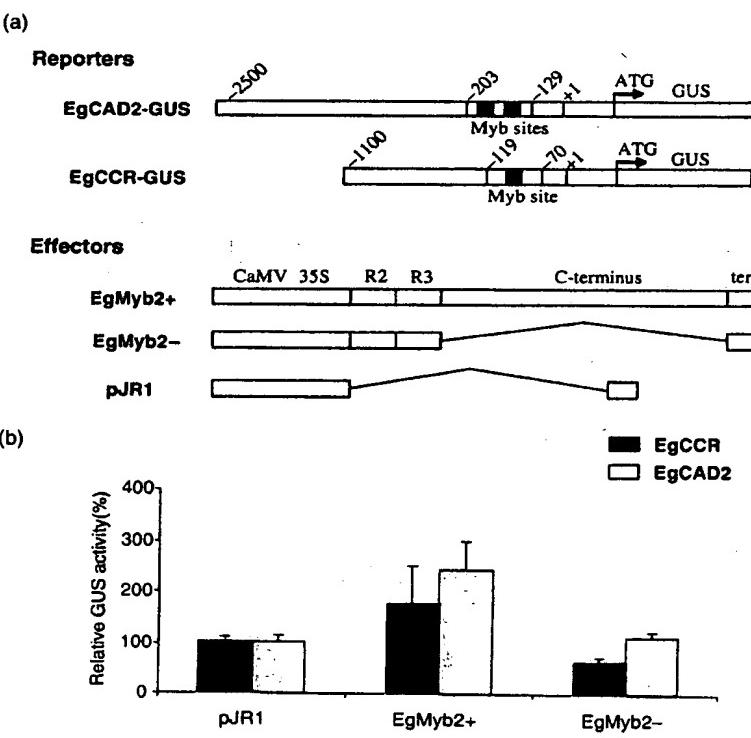
(b) Nucleotide sequences of AC elements found in *EgCCR* and *EgCAD2* promoters compared with the MBSIIIG consensus site (Romero et al., 1998).

(c) EMSA in which the indicated radiolabelled promoter fragments were incubated with GST-EgMYB2 recombinant protein in the absence (lanes 1, 5) or presence of 100x molar excess of non-specific (lanes 3, 8), [-203-129] *EgCAD2* (lanes 2, 7) or [-119-70] *EgCCR* (lanes 4, 6) unlabelled competitors. Amounts of GST-EgMYB2 protein were 100 and 30 ng for *EgCAD2* and *EgCCR* promoter fragments, respectively. No DNA-binding activity was observed using recombinant GST alone (data not shown).

Figure 6. Effects of EgMYB2 on transcriptional activities of the *EgCAD2* and *EgCCR* promoters *in vivo*.

(a) Schematic maps of the reporter and effector constructs. CaMV35S, 35S promoter; GUS, *uidA* coding region; (+1), transcription start site; R2R3, MYB DNA-binding domain; ter, nopaline synthase terminator.

(b) Results from co-transfection experiments in tobacco leaves. Agrobacteria containing effector and reporter constructs were co-infiltrated in tobacco leaves. Data represent mean values and standard deviations of three independent experiments, each containing at least three replicates. GUS activity is expressed as percentage of GUS activity relative to control (pJR1, 'empty' vector co-transfected with reporter constructs). Activations of *EgCAD* and *EgCCR* promoters are statistically significant relative to controls (Student's $P < 0.001$ and 0.04, respectively).



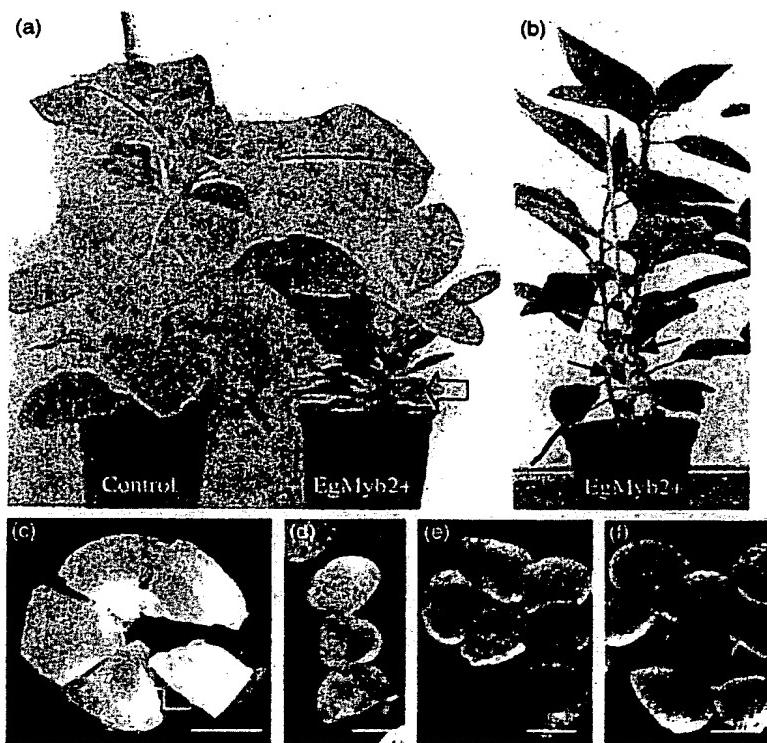


Figure 7. Phenotypic changes induced by *EgMYB2* ectopic expression in tobacco.

(a) Control plant and *EgMyb2⁺* primary transformant 2 weeks after transfer to the glasshouse. (b) *EgMyb2⁺* primary transformant 6 weeks after transfer to the glasshouse. Note the presence of two main stems (arrows).

(c) Pattern of xylem coloration in hand-cut stem sections of four *EgMyb2⁺*-independent primary transformants relative to control stem section (open arrow), scale 0.5 cm.

(d-f) Phloroglucinol staining of seeds (scale 0.8 mm); seeds of control (d); *EgMYB2⁺* primary transformant 2.7 (e); and transformant 2.18 (f).

agreement with the 50% germination rate (Figure 7e). All seeds of 2.18 which were unable to germinate stained more intensely than control seeds. Staining was concentrated in the region of the micropylar testa, where the radicle is known to emerge (Figure 7f).

The main phenotypic characteristics of primary transformants 2.7 and 2.16 (reduced plant size, loss of apical dominance, orange coloration of xylem) were associated with transgene expression, as these characteristics were maintained in the *T₁* and *T₂* progeny.

EgMYB2 increases xylem secondary cell wall thickness

Cytological observations of xylem were performed on glasshouse-grown tobacco stem sections, either at low magnification using epifluorescence microscopy (Figure 8a,b) or at higher magnification using confocal microscopy (Figure 8c,d). At low magnification a significant increase in the number of lignified phloem fibres and xylem vessels was observed in some transformants, such as 2.18 (Figure 8b), compared with controls (Figure 8a).

Observations under confocal microscopy revealed that the xylem cell walls were thicker in the *EgMYB2⁺* transformants (Figure 8d) compared with controls (Figure 8c). Measurements of fibre cell wall thickness indicate a dramatic

thickening of xylem cell walls in transformant plants ($4.9 \pm 0.9 \mu\text{m}$) compared with controls ($3.5 \pm 0.8 \mu\text{m}$) (Figure 9). Student's test showed that the difference between the two populations is highly significant with $P < 0.001$ and $n = 500$. Observations of cell walls at the ultrastructural level by electron microscopy allowed us to demonstrate that the increase in cell wall thickness in *EgMyb2⁺* plants was due to an increase in the thickness of the middle S2 layer of the secondary cell wall (compare Figure 8g,h with controls in Figure 8e,f), whereas the S1 external and S3 internal layers appeared normal.

To gain information on the lignin content and composition within the xylem tissues, staining was performed using phloroglucinol reagent (Figure 8i,j); Maüle reagent (Figure 8k,l); and potassium permanganate for the visualization of lignin distribution (Figure 8m,n). The intensity of staining was always higher in transformed plants, whichever reagent was used, and appeared uniform across the thickened cell wall. The increase in reactivity of the cell walls using phloroglucinol and potassium permanganate could indicate a higher lignin content in xylem, which could be related to increased cell wall thickness. On the other hand, the strong reactivity to the Maüle reagent, which primarily stains syringyl lignin indicative of S units, suggests a higher S-unit composition in the lignin from transgenic lines.

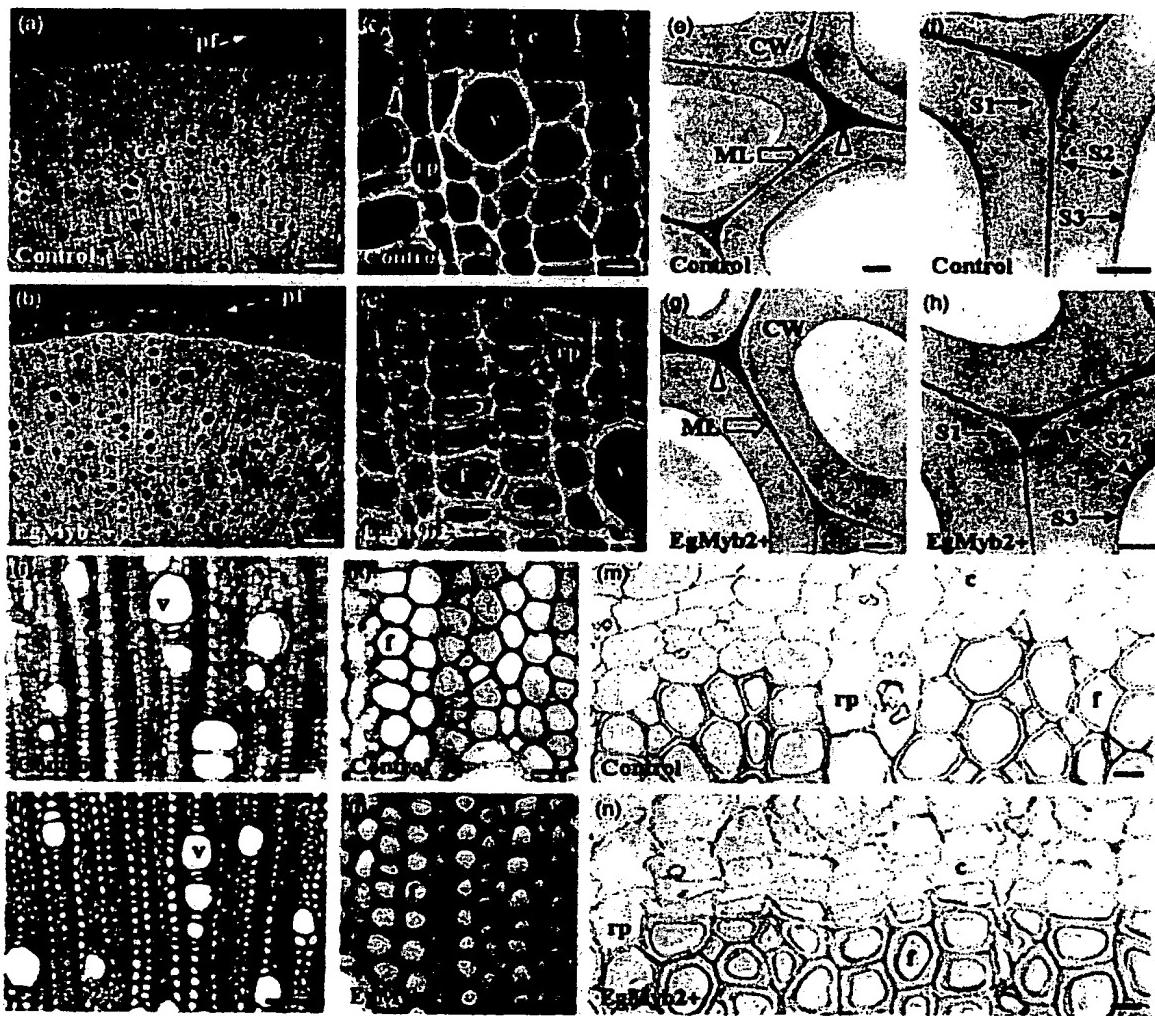


Figure 8. Cytological effects of *EgMYB2* over-expression in stem sections.
 (a–d) Autofluorescence of xylem tissues on hand-cut stem sections under epifluorescence microscopy (a,b) and confocal microscopy (c,d) for control plant (a,c) and *EgMYB2*⁺ transformant (b,d).
 (e–h) Electron micrographs of KMnO₄-stained ultrathin stem sections of control (e,f) and *EgMyb2*⁺ transformant (g,h).
 (i–n) Phloroglucinol (i,j), Maule (k,l) and potassium permanganate (m,n) stainings on transverse sections of control plants (i,k,m) and *EgMyb2*⁺ transformant (j,l,n). v, xylem vessel; rp, ray parenchyma; f, xylem fibres; pf, phloem fibres; c, cambial zone. S1–S3, layers within xylem fibre cell wall. Open arrows, middle lamella area (ML); arrowheads, cell junctions. Scale bars, 100 (a,b); 50 (i,j), 30 (k,l); 20 (c,d,m,n); 1 μm (e,f,g,h).

EgMYB2 controls the co-ordinated expression of genes involved in the lignin biosynthetic pathway

The ability of *EgMYB2* to alter the expression of a complete set of genes involved in lignin biosynthesis (*PAL*, *C4H*, *4CL*, *C3H*, *HCT*, *CCoAOMT*, *F5H*, *COMT*, *CCR*, *CAD*) was assessed by quantitative RT-PCR using RNA isolated from leaves of the transgenic lines described above. The assays were

normalized to actin transcript levels. Figure 10 shows the relative levels of transcript accumulation found in glasshouse-grown *EgMyb2*⁺ plants relative to control plants. Transcription of the two genes involved in the early steps of phenylpropanoid metabolism, *PAL* and *C4H*, was not significantly affected by the over-expression of *EgMYB2* and the third gene involved, *4CL*, appeared moderately (about threefold) activated. In marked contrast, all the genes

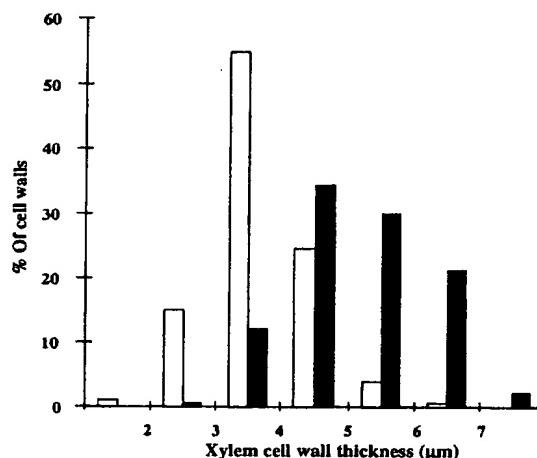


Figure 9. Effect of *EgMYB2* ectopic expression on the thickness of xylem fibres cell walls.

Frequency graph for comparison of cell wall thickness distribution (percentage of cell walls) between controls (open bars) and *EgMyb2*⁺ plants (solid bars) within different classes. (0–2), thickness <2 μm; (2–3), thickness 2–3 μm, etc. 500 measurements were performed on semi-thin stem sections observed under bright light from two control plants and four independent primary transformants, using IMAGE-PRO PLUS software. Means and standard deviations, 4.9 ± 0.8 μm for *EgMyb2*⁺ plants; 3.5 ± 0.8 μm for controls. The difference between the two populations is highly significant (Student's $P < 0.001$).

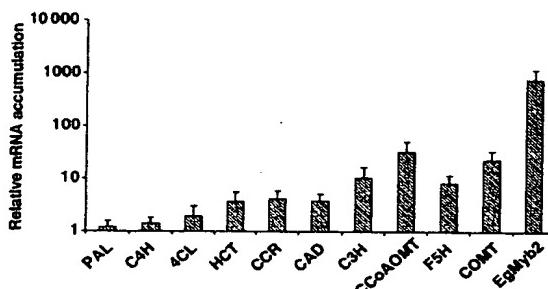


Figure 10. Quantitative RT-PCR analysis of transcript accumulation in transgenic tobacco plants over-expressing *EgMYB2*.

PAL, *C4H*, *4CL*, *C3H*, *HCT*, *COMT*, *F5H*, *CCoAOMT*, *CCR*, *CAD* and *EgMYB2* mRNA accumulation was assessed by quantitative RT-PCR in leaves of four independent primary transformants. Transcript levels were normalized relative to the actin expression level as internal standard. Results expressed as mean and standard deviation relative to control plant the expression level of which has been assigned the value = 1 on the logarithmic scale.

encoding steps committed to monolignol biosynthesis were dramatically upregulated. Transcripts of the genes involved in conversion of esters to aldehydes, and aldehydes to alcohols (*HCT*, *CCR*, *CAD*) were about fivefold more

abundant in transgenic *EgMyb2*⁺ plants than in control plants, and transcript levels of the genes involved in the differential pathways leading to the three monolignol monomers (*C3H*, *CCoAOMT*, *F5H*, *COMT*) were up to 40-fold higher. Upregulation of the monolignol biosynthesis genes was also observed in stem tissue of the transgenic plants, but the extent was about twofold lower than in leaves, probably due to the fact that these genes are already activated by the endogenous tobacco MYB protein in stems.

EgMYB2 mainly controls the monomeric composition of lignin

To test the effect of *EgMYB2* on lignin content and composition, we performed biochemical lignin determinations on the selected mature primary transformants. Despite the cytological observations and gene expression analysis described above, the data presented in Table 1 reveal that the Klason lignin content of the transformants does not differ substantially from the control level.

Lignin structure was investigated by thioacidolysis, a method that allows extraction of the lignin units involved in β-O-4 bonds (Lapierre *et al.*, 1986). The total yield of G and S lignin-derived main monomers recovered from the cell wall residue and referred to the Klason lignin was found to be similar in the transformants and control series. This result shows that the content of lignin units involved in uncondensed β-O-4 bonds is not significantly affected by the transgene. However, the S/G ratio was found to be significantly higher in the lignin extracted from *EgMyb2*⁺ plants (1.27 ± 0.11 relative to control 1.09 ± 0.01 , with Student's $P < 0.05$), essentially due to an increase in the amount of S units (Table 1). This result is consistent with the higher Maule staining of the xylem samples from transgenic plants relative to the controls (Figure 8k,l). Interestingly, it is also related to the expression levels of the genes encoding *CCoAOMT* and *COMT*, enzymes involved in the methylation steps leading to the G and S monomeric units. Indeed, the highest S/G ratio in lignin (1.46, 34% higher than in control plants) was found in the transgenic plant in which the *COMT/CCoAOMT* expression ratio was highest (2.08). Conversely, the lowest S/G ratio among the transformants (1.18) was found in the plant in which the *COMT/CCoAOMT* expression ratio was lowest (0.16). The higher S/G value of the transformants relative to controls could be confirmed on *T₂* plants (data not shown). Together, these data suggest that *EgMYB2* controls the *COMT/CCoAOMT* ratio which, in turn, has a direct consequence for the S/G monomeric ratio.

Discussion

As part of a programme aimed at identifying regulators of lignin biosynthesis, we have characterized a new R2R3 MYB

Table 1 Lignin analysis in *EgMyb2⁺* plants

| Plant | Klason | S | G | S + G | S/G |
|--------------------------------|--------------|---------------|------------|------------|-------------|
| 2.7 | 20.91 | 919 | 749 | 1668 | 1.23 |
| 2.24 | 19.24 | 1019 | 867 | 1886 | 1.18 |
| 2.16 | 20.23 | 1070 | 854 | 1924 | 1.25 |
| 2.18 | 20.38 | 1077 | 881 | 1958 | 1.22 |
| 2.19 | 19.73 | 1163 | 798 | 1961 | 1.46 |
| Mean <i>EgMYB2⁺</i> | 20.10 ± 0.64 | 1049.6 ± 89.5 | 829.8 ± 55 | 1879 ± 122 | 1.27 ± 0.11 |
| C06 | 19.02 | 953 | 874 | 1827 | 1.09 |
| C30 | 19.7 | 1038 | 938 | 1976 | 1.1 |
| C11 | 18.79 | 856 | 787 | 1643 | 1.09 |
| Mean control | 19.17 ± 0.47 | 949 ± 91 | 866.3 ± 75 | 1815 ± 166 | 1.09 ± 0.01 |

Five independent *EgMYB2⁺* plants and three control plants were analysed for lignin content using the Klason method. Amount of lignin (referred to as Klason) is expressed as weight percentage of dried cell wall residue. Lignin composition was determined by thioacidolysis. Amounts of S and G monomers are expressed as $\mu\text{mol g}^{-1}$ Klason lignin. Student's t-test showed that differences between controls and transgenics were significant with $P = 0.05$ for the S/G ratio. In contrast, the difference observed for the Klason lignin content does not appear as significant ($P = 0.07$).

gene (*EgMYB2*) from *Eucalyptus* that is highly and preferentially expressed in secondary xylem. This gene is single copy and maps to a QTL influencing lignin quantity. The *EgMYB2* protein is able to bind specifically the regulatory regions of the *EgCCR* and *EgCAD2* promoters *in vitro*, and to increase their transcription as shown by transient expression experiments. Together, these results raised the possibility that *EgMYB2* might control the co-ordinated expression of genes committed to the monolignol biosynthetic pathway. This hypothesis was further supported by transcript analysis of phenylpropanoid genes in transgenic tobacco plants over-expressing *EgMYB2*, which revealed significant increases in transcript abundance of genes known to be involved in the monolignol-specific portion of the pathway, but not those of the general phenylpropanoid pathway (*PAL*, *C4H*). The genes involved in conversion of esters to aldehydes, and of aldehydes to alcohols (side-chain modification), *HCT*, *CCR* and *CAD*, were about fivefold up-regulated, whereas the genes involved in the differential pathways leading to the monolignol monomers (ring modification), *C3H*, *F5H*, *CCoAOMT* and *COMT*, were up to 40-fold upregulated.

As a consequence of the high increase in transcript abundance of the genes encoding enzymes involved in ring modification, the major main effect of *EgMYB2* was to alter the lignin monomeric composition. In angiosperms, the type of monomeric units within a lignin polymer depends on the degree of methylation of either the 3-hydroxyl groups or both 3-hydroxyl and 5-hydroxyl groups, leading to G and S units, respectively. *CCoAOMT* is believed to play an essential role in the synthesis of G units as well as in the supply of substrates for the synthesis of S units, whereas *COMT* essentially controls the biosynthesis of S units (Pincon *et al.*, 2001; Zhong *et al.*, 1998, 2000). In *EgMyb2⁺* plants we observed an increase in S/G ratio, mainly due to an increase

in S units which probably results from the strong activation of *COMT*.

At the phenotypic level, plants over-expressing *EgMYB2* were characterized by reduced size in comparison with controls. With regard to this observation, it is interesting to draw a parallel with the recent findings of Kirst *et al.* (2004) showing that in an *E. grandis* back-cross family the genomic regions regulating growth are the same as those controlling lignin content and composition. Indeed, a negative correlation was found between transcript levels estimated for the lignin genes and growth. The most significant correlations were found for *F5H*, *C4H*, *C3H*, *COMT*, *CCoAOMT* and *CAD* (*CCR* was not analysed). It is worth noting that, as in the tobacco over-expressing *EgMYB2*, S units were more abundant in slow-growing trees (38% increase) compared with fast-growing trees. It is possible that higher carbohydrate consumption for more lignin synthesis may have a negative effect on growth rate.

No significant increase in the Klason lignin content relative to the cell wall residue was detected in transgenic tobacco over-expressing *EgMYB2*, in contrast to what could be expected from cytological analyses (intensity of phloroglucinol staining), and from the degree of activation of lignin biosynthetic genes. One plausible explanation for this apparent discrepancy relies on the very significant increase (40%) in thickening of the xylem cell walls, which has been observed whatever the method used for microscopic inspection. This thickening, assigned to the S2 layer of the secondary cell walls by electron microscopy, might be the consequence of an increase in the content of at least one of the other major constituents of secondary cell wall: cellulose and hemicelluloses, which would result in underestimating the increase in lignin content relative to cell wall residue.

Interestingly, an increase in phloroglucinol staining suggesting the presence of a higher lignin content or related condensed phenolics was observed not only in the walls of xylem cells, but also in the seed testa. In addition, the fact that the testa develops from the integuments of the ovule, and is therefore a maternal diploid tissue, provides an explanation for the complete absence of germination in the most extreme lines. It is likely that an alteration of cell wall composition occurred in the testa, probably preventing the action of hydrolases needed to complete germination and to allow the radicle to emerge.

At the protein level, the presence of a motif conserved in the C-terminal region of *EgMYB2* from *Eucalyptus*, *Popt1:4971* from cottonwood and *AtMYB83* from *Arabidopsis* may indicate functional similarity between these proteins and therefore define a new subgroup of MYB transcription factors. It is worth noting that neither the *Arabidopsis* MYB gene *AtMYB83* (nor its close sequence *AtMYB46*) has been assigned any position among the subgroups defined in the *Arabidopsis* MYB family (Kranz *et al.*, 1998). This motif was not found in the C-terminal domain of *PtMYB4*, a MYB gene isolated from a gymnosperm (*Pinus taeda*), highly expressed in xylem and involved in the regulation of lignification (Patzlaff *et al.*, 2003). When over-expressed in transgenic tobacco, both *EgMYB2* and *PtMYB4* act as transcriptional activators of genes committed to the lignin biosynthetic pathway, suggesting that their DNA-binding domains have similar selectivity. The increase in lignin content was higher in *PtMYB4* than in *EgMYB2* over-expressing plants. This might be due, at least in part, to the higher strength of the promoter used (double 35S CaMV) to direct *PtMYB4* expression compared with the single 35S CaMV used to drive *EgMYB2* expression. The relative weakness of the latter in xylem has been reported in other studies (Franke *et al.*, 2000). It should also be noted that ectopic expression of *PtMYB4* induces lignification in some cell types that normally do not lignify, such as cells from the pith. Such ectopic lignification was not observed in *EgMyb2⁺* plants, although in some transformants a higher number of lignified fibres were noticed. Although *PtMYB4* and *EgMYB2* share a number of common features, they also show some differences, suggesting that they are not functional homologues when working in their natural species. For instance, we have shown in *EgMyb2⁺* plants that among the most highly activated genes were those encoding enzymes responsible for control of the S/G ratio. Such a role would be unlikely for *PtMYB4*, as lignins from pine do not contain S units.

Together, these results strongly suggest that *EgMYB2* is a positive regulator of secondary cell wall formation and lignin biosynthesis. Moreover, its co-localization with a QTL for lignin content renders it a good candidate for controlling lignin profiles that could be exploited in *Eucalyptus*-breeding programmes.

Experimental procedures

Recombinant DNA methods

Routine DNA methods were used according to Sambrook *et al.* (1989). DNA sequencing was performed with an ABI Prism 3700 DNA sequencer, using the ABI PRISM Dye terminator Cycle Sequencing Ready Reaction Kit (Amersham Pharmacia Biotech, Orsay, France).

cDNA library screening

Approximately 600 000 pfu of an amplified cDNA library from *E. gunnii* xylem in lambda ZAPII (Lacombe *et al.*, 1997) were blotted onto nitrocellulose membranes following the protocol recommended by the manufacturer (Stratagene, La Jolla, CA, USA), and screened using a consensus 38-mer oligonucleotide [5'-tkccmgaagracmgayaatgaatcaagaaytaytgc] corresponding to a highly conserved motif in the R3 domain of MYB factors [PGRTDNEIKNYWN] (Jackson *et al.*, 1991), labelled with ³²P-ddATP (Amersham) and terminal deoxynucleotidyl transferase (Boehringer Mannheim, Meylan, France). Filters were hybridized overnight at 42°C in 5 × SSPE, 0.25% dry milk powder and 0.05% SDS. Washes were performed at 42°C in 2 × SSC, 0.1% SDS. Plaque-purified positive clones were converted into phagemids (pBluescript SKM13+) following Stratagene's instructions.

RNA isolation

Total RNA was extracted from various *Eucalyptus globulus* tissues harvested on 7-month-old glasshouse-grown plants as recommended by Southerton *et al.* (1998). Total RNA was extracted from leaves of mature glasshouse-grown wild-type and transgenic tobacco plants using the Extract-all kit (Eurobio, Paris, France). In both cases, total RNA was treated with RNase-free DNase I (Invitrogen, Cergy Pontoise, France) and purified on columns (Qiagen, RNA Mini Kit). RNA quality and quantity were checked by agarose gel and spectrophotometry.

Quantitative real-time RT-PCR

First-strand cDNA was synthesized from 1 µg RQ1 DNase-treated total RNA in a 20 µl reaction mixture containing 500 ng oligo dT₁₂₋₁₈, 0.5 mM dNTPs, 1 µl RNasin and 200 U SuperScript II reverse transcriptase, according to the manufacturer's instructions (Invitrogen). After incubation at 42°C for 1 h and at 65°C for 15 min, the cDNA was purified on Sephadex G50 columns in a 100 µl final volume. 2 µl cDNA was used as template in a quantitative real-time PCR assay (15 µl) performed on the LightCycler Instrument using the LightCycler FastStart DNA Master^{PLUS} SYBR Green I reaction mix (Roche Applied Science, Meylan, France). After a initial denaturation step of 8 min at 95°C, 45 cycles of 15 sec at 95°C, 10 sec at 56–60°C (0–4°C below melting temperature, *T_m*) and 12 sec at 72°C were performed. Amplification specificity was checked by melting-curve analysis, and PCR efficiency was determined using standard curves constructed with serial dilutions of PCR products as templates. Actin was used as internal control for tobacco leaf samples. The amount of *EgIDH* transcript checked in different tissues of *Eucalyptus* exhibited cycle threshold values (*C_t*) of 20.13 cycles (mean) ± 0.51 (standard deviation), within the experimental error range of real-time PCR. Therefore *IDH* expression does appear constitutive in the different *Eucalyptus* tissues examined and was used as an internal

control. Quantification of expression ratios was performed according to the mathematical model developed by Pfaffl (2001). Primers and amplicon sizes: *Eucalyptus*, *EgMYB2* (152 bp; upper 5'-ggggatggagatttgtaca, lower 5'-aacggcccttccactaaaga); *EgIDH* (115 bp; upper 5'-ctgtcggaatctgtatgeaca, lower 5'-tcactctggacatccatca); *Tobacco* – in the case of multigene families primers have been designed to hybridize to all genes of the class postulated to have a role in lignin biosynthesis: *PAL* (94 bp, primers common to the two class I genes AB008200, X78269, upper 5'-gacaaagt-gttcacagcaat, lower 5'-taacagatwgaaagaggagc); *C4H* (124 bp, D. Werck-Reichhart, IBMP, Strasbourg, France, personal communication, upper 5'-tcaacacataatggbaatgc, lower 5'-acttggacgtttgttca); *4CL* (89 bp, primers common to the two class I and class II genes U50845, U50846, upper 5'-cttctcaaccatccaaat, lower 5'-ctaacaacaaaagccactgg); *HCT* (127 bp, AJ507825, upper 5'-ggctgcataatccatgtatgc, lower 5'-gcaacatggactgcata); *C3H* (112 bp, primers common to the two very close genes; C. Chapple, Purdue University, IN, USA, personal communication, upper 5'-tggct-gaggtgtatcaagaa, lower 5'-tatggaggatggggaaatgc); *CCoAOMT* (96 bp, primers common to the four class I genes U38612, U62734, U62735, U62736, upper 5'-acaccstatggatggatca, lower 5'-cctgttgagttcaatacga); *F5H* (93 bp, primers common to two genes (unpublished data), upper 5'-gaaactctacactgttccccc, lower 5'-tgactttggccaaatatgtt); *COMT* (132 bp, primers common to the two class I genes X74452, X74453, upper 5'-ctgcaataatggaaatgtat, lower 5'-cagtcctttttgtcttc); *CAD* (142 bp, primers common to the two very close genes X62343, X62344, upper 5'-ctggggagaaagagcatca, lower 5'-cctctccatgtcgttgtca); *CCR* (139 bp, C. Halpin, University of Dundee, UK, personal communication, upper 5'-atgtgacgaaatgggtta, lower 5'-tttagaaatggaaatgtac); *Actin* (139 bp, consensus primers to all tobacco constitutive actin genes, upper 5'-atgtkctcgttgtggct, lower 5'-cctcaatccagacactgt).

Expression of GST-EgMYB2 in *E. coli*

The *EgMYB2* cDNA was recovered from the bluescript plasmid pBSK-*EgMYB2* using *Eco*RI and *Xba*I and directionally cloned into the expression vector pGEX-5X-1 (Amersham-Pharmacia). The in-frame fusion 3' to the *Glutathione S-Transferase (GST)* gene was checked by sequencing. The resulting plasmid was introduced in *E. coli* strain BL21 and induction of the GST-*EgMYB2* fusion protein was realized by adding Isopropyl β-D-thiogalactoside (Sigma-Aldrich, St. Quentin, France) to a final concentration of 0.1 mM. After growth at 20°C for 6 h, cells were lysed in buffer: 20 mM Tris pH 7.5, 1 mM EDTA, 10% glycerol, 0.1% NP40, 100 mM PMSF, 10 µg ml⁻¹ leupeptin; 10 mM β-mercaptoethanol, 10 mM MgCl₂, 2 mg ml⁻¹ lysozyme, 5 U DNaseI (RQ1, Promega, Charbonnières, France). The fusion protein was purified from the soluble phase using glutathione-Sepharose 4B matrix following the supplier's instructions (Amersham-Pharmacia). Protein concentration was estimated with Bradford reagent (Bio-Rad, Marnes la Coquette, France) and proteins extracts were analysed by SDS-PAGE and Western blotting using a mouse primary antibody anti-GST and a secondary antibody (IgG anti-anti-GST of mouse) conjugated with peroxidase.

Electrophoretic mobility shift assay

Vectors containing the *EgCAD2* (Feuillet *et al.*, 1995) or *EgCCR* (Lacombe *et al.*, 2000) promoters were used to amplify by PCR the [-203–129] *EgCAD2* regulatory fragment with the upper 5'-tcgtcgatggctaaaaaacaatgttgc-3' and lower primer 5'-ggcgaaaaatgtacatctcgacaaac, and the [-119–70] *EgCCR* regulatory fragment with the upper primer 5'-ggctcgagggggcgc and the lower primer

5'-gactcgagtttaccaaga, all the primers containing *Xba*I restriction sites. The PCR products were cloned in pGEM-T vector (Promega) and checked by sequencing. After *Xba*I digestion the resulting *EgCAD2* and *EgCCR* regulatory fragments were purified on agarose gels and 100 ng were 3'-end labelled for 30 min at 37°C with the Klenow fragment of DNA polymerase I (5 U) in a final volume of 20 µl with 33 µM of each dATP, dTTP, dGTP and 4 µl α-³²PdCTP (10 mCi ml⁻¹). The labelled fragments were purified on a 4.8% polyacrylamide gel and eluted in water overnight at 4°C. Binding reactions were performed in a total volume of 25 µl, with 5000–10 000 cpm labelled DNA fragments (20–30 fmol), 30–100 ng purified GST-*EgMYB2* or GST alone, 10 mM Tris-HCl pH 8, 150 mM NaCl, 10% glycerol and 500 ng poly dIdC-poly dIdC (Gibco-BRL, Paris, France). For competition experiments, non-radioactive competitors were added to a 100-fold molar excess ratio relative to the probe. The binding reactions were incubated for 30 min at room temperature and analysed on a 4.8% polyacrylamide gel as previously described by Lacombe *et al.* (2000).

Binary constructs for transformation

The *EgMYB2* cDNA was subcloned as a *Kpn*I-*Xba*I fragment into the pGEM-T vector (Promega) and the sequence was checked. The 1.4 kb cDNA fragment was cloned into the binary vector pJR1 (Piquemal *et al.*, 1998) under the control of the 35S CaMV promoter, generating the *EgMyb2*⁺ construct. For downregulation we generated a dominant negative construct. The plasmid pGEMT-*EgMYB2* (mentioned above) was digested with *Kpn*I and *Pst*I and the resulting 0.5 kb fragment corresponding to the DNA-binding domain (DBD) was placed under the control of the 35S CaMV promoter in an intermediary vector pBOB13 (EL, unpublished data). After digestion by *Hind*III and *Eco*RI, the [35S promoter-*EgMYB2* DBD-Nos terminator] cassette was inserted into the binary vector pBin19, leading to the construct *EgMYB2*⁻. Using the freeze-thaw procedure (Holsters *et al.*, 1978), the constructs *EgMyb2*⁺ and *EgMyb2*⁻ were introduced into *Agrobacterium tumefaciens* strain LBA4404 for stable transformation, and/or into strain C581pCH3 for transient co-transfection experiments.

Co-transfection experiments

Co-transfection experiments were performed essentially according to the method of Yang *et al.* (2000). *Agrobacterium* strains C581pCH3, containing either a binary effector plasmid or a reporter construct, were co-infiltrated in near fully expanded leaves of tobacco plants using a 1 ml syringe. After agro-infiltration, plants were maintained in a growth chamber at 22°C under 16 h light for 3 days. Quantitative GUS assays were carried out on the infiltrated zone using 4-methylumbelliferyl-β-D-glucuronide as substrate (Jefferson, 1987). Protein concentrations were determined by the Bradford method (Bio-Rad). GUS activities were estimated as the mean of three independent assays, each containing at least three replicates.

Tobacco plant transformation

Tobacco (*Nicotiana tabacum* cv. Samsun NN) was transformed by a modification of the leaf-disc method (Horsch *et al.*, 1985). Regeneration and propagation procedures were as described by Piquemal *et al.* (1998). More than 15 independent tobacco transformants were generated for each construct, propagated *in vitro* and transferred to the glasshouse. The presence of the transgene was confirmed by PCR on genomic DNA using specific primers for kanamycin

resistance and for MYB genes (described above). F_1 seeds obtained by self-pollination of transformants were harvested and selected further on germination medium containing kanamycin ($500 \mu\text{g ml}^{-1}$). The sterilization treatment was for 2 min in ethanol 70% followed by 5 min NaOCl, 5%.

Microscopy and cell imaging

Transverse sections (100 μm thick) in the lower part of tobacco stems were obtained using a vibratome (Microcut H1250; Energy Beam Science Inc., St. Louis, MO, USA). They were observed either under UV excitation (excitation filter BP 340–380 nm, suppression filter LP 430 nm) or under bright-field after phloroglucinol (Wiesner reagent) and Mäule staining for lignin visualization. Other samples, dehydrated in ethanol, were embedded in Spurr's epoxy resin. Semi-thin (1–2 μm) and ultrathin sections (90 nm) were obtained using an ultramicrotome (Reichert UltraCutE; Leica Microsystems, Rueil Malmaison, France). Semi-thin sections, mounted on glass slides, were observed in confocal microscopy (LSM SP2; Leica) using the 488 nm ray line of the argon laser. The emitted light was collected between 500 and 550 nm. Other semi-thin and ultrathin sections were treated by KMnO₄ and observed either under bright-field or with an electron microscope at 80 kV (Hitachi, Naka, Japan). In optical microscopy, images were acquired using a CCD camera (Color CoolView; Photonic Science, Milham, UK). The thickness of the xylem cell walls was determined by image analysis (IMAGE PROPLUS software; Media Cybernetics, Silver Spring, MD, USA). Micrographs of seeds were acquired with a stereomicroscope (MZFLIII; Leica) equipped with a CDD camera (DC200; Leica).

Lignin analysis

Basal parts of stems of control and transgenic mature plants were harvested and frozen in liquid nitrogen. After lyophilization the stem samples were ball-milled to a fine powder and extracted as previously described by Piquemal *et al.* (1998) for subsequent determinations of Klason lignin contents using the Klason technique (Dence, 1992). Thioacidolysis was performed using the method of Lapierre *et al.* (1986).

Gene mapping and QTL analysis

Genetic mapping of EgMYB2 was performed using an interspecific F_1 hybrid progeny (201 full sibs) between *E. urophylla* (female) and *E. grandis* (male) (Verhaegen and Plomion, 1996). Conformation polymorphism was detected using the SSCP technique as described previously by Gion *et al.* (2000) with specific primer pairs (upper 5'-tccaattccacaagacatacg, lower 5'-gtgggggaacagaaaaactcg). In comparison with the *E. gunnii* EgMYB2 sequence, four and six nucleotides were different in the *E. urophylla* and *E. grandis* sequences, respectively, indicating that both parents were heterozygous at this locus. Using a migration temperature of 15°C for 15 h electrophoresis, four bands were obtained, segregation of which in the progeny was consistent with the patterns observed in the parents. In order to map the newly genotyped SSCP EgMYB2 marker to linkage maps previously established using RAPD markers for both parents (Verhaegen and Plomion, 1996; Verhaegen *et al.*, 1997), linkage analysis was performed using the MAPMAKER programme (Whitehead Institute, Cambridge, MA, USA) with a minimal linkage LOD of 6 and a maximum recombination fraction θ of 0.30. Assessments of lignin content using the Klason method was made

on the 201 progenies used for establishing both genetic maps at 62 months, which corresponds to harvest age in commercial *Eucalyptus* plantations. The lignin content presented a normal distribution in the progeny studied. The QTL analysis was performed on each parental map under the back-cross model. Both the interval-mapping methods implemented in MAPMAKER/QTL (maximum likelihood) and QGENE (linear least squares; Whitehead Institute) with a threshold of 1.7 were used to declare a putative QTL for lignin content.

Sequence data from this article have been deposited with the EMBL/GenBank data libraries under accession number AJ576023.

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